DEVELOPMENT AND FLIGHT EVALUATION OF ACTIVE CONTROLS IN THE L-1011

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SUMMARY

This paper discusses a cooperative NASA/Lockheed program investigating active controls in the Lockheed L-1011 for increased energy efficiency. The tasks involve (1) active wing load alleviation for extended span, increased aspect ratio, and (2) active stability augmentation with a smaller tail for reduced drag and weight. Tests to date include flight tests of active wing load alleviation on the baseline aircraft and moving-base piloted simulation developing criteria for stability augmentation. Tests with extended span will be accomplished later this year.

Active controls in commercial transports have developed in an evolutionary manner. Some examples are the L-1011 Autoland automatic landing system, and the L-1011 yaw damper permitting a 20% reduction in vertical fin design loads. These developments set up some of the basic principles and techniques for active controls in commercial transports: probability-based analyses for equivalent safety, and definition and mechanization of redundancy requirements. The extensions to wing load alleviation and to relaxed static stability are logical, and the results to date indicate that they are easily accomplishable by use of the proper technologies.

Load Alleviation

The active load alleviation system uses symmetric motions of the outboard ailerons for Maneuver Load Control (MLC) and Elastic Mode Suppression (EMS), and stabilizer motions for Gust Alleviation (GA). The L-1011 is particularly adaptable to wing load alleviation because its outboard ailerons remain effective at high speed. The control laws were derived, after initial explorations of optimal control theory, by use of large-scale maneuver loads, flutter, and gust loads programs. Interactive graphics was an important element of the process.

The active controls computer and hardware were tested in the Vehicle Systems Simulator (VSS) at Lockheed's Rye Canyon research facility and then installed in the house L-1011. The flight tests went smoothly, without any delays caused by the active systems. Open-loop transfer function tests showed excellent test/analysis correlation for the aircraft dynamic response to symmetric aileron and stabilizer drives, and closed-loop transfer function tests showed the active systems performed as predicted. Wind-up turns and pull-up/push-over maneuvers verified the maneuver load control. Flight tests in turbulence verified the effectiveness of the active controls in reducing gust-induced wing loads.

It was concluded that the use of the large-scale production loads, flutter and gust response programs had produced excellent results in deriving the control laws and predicting airplane response. A corollary conclusion was that the data base built up from ground, flight and wind-tunnel tests was entirely adequate.

Stability Augmentation

The flight dynamics of an L-1011 derivative having a 40% smaller horizontal tail were analyzed using a continuous systems modeling program. These analyses covered the complete flight envelope and identified areas for concentration in flight simulation and augmentation design. Also, these data were studied to determine the applicability of various handling qualities criteria. Criteria for augmentation system design, and unaugmented flying qualities were selected. These criteria utilized current L-1011 flying qualities as a basis.

An augmentation system consisting of a simple pitch rate damper supplemented by a column feed forward for control response tailoring was devised.

Pilot-in-the-loop testing was conducted on a moving base flight simulator. Three pilots flew the small-tail simulation model and a base-line having the current L-1011 tail. Testing was conducted with static margin and air turbulence level as variables.

Results from these piloted simulations show pilot ratings in the acceptable range for an unaugmented small-tail airplane with static margin of 5% even in heavy turbulence. For the small-tail airplane with neutral static stability, the pitch-rate damper augmentation system without feed-forward provides flying qualities as good as those of the unaugmented big-tail airplane at its mid-c.g. condition.

INTRODUCTION

Active controls in commercial transports have developed in an evolutionary manner from flight-path-management systems such as the L-1011 Autoland automatic landing system to load alleviation systems such as the L-1011 yaw damper, which allowed a 20-percent reduction in vertical fin design loads. These developments were important in setting up some of the basic principles and techniques for active controls in commercial transports: the use of probability-based analyses, and definition and mechanization of redundancy and monitoring requirements.

Both the Autoland and yaw damper active control systems were included in the basic certification of the L-1011 in 1972. Building on this base, research was started in 1974 on use of active controls for wing load alleviation and for stability augmentation. Although the initial objective of the load alleviation was an increase in gross weight using existing wing structure - an increase of 12 percent was found possible - the rising costs of fuel soon made it apparent that load alleviation could best be used to increase the wing span for improved fuel efficiency. The objective of the stability augmentation studies was drag reduction by use of a smaller horizontal tail and reduced stability margin. Studies and wind tunnel tests indicated that the extended span and the smaller tail would each result in a 3 - 3-1/2 percent fuel saving, for a combined saving of 6 - 7 percent.

Both the load alleviation and the stability augmentation studies are now partially funded by NASA's Aircraft Energy Efficiency (ACEE) Program, reference 1, through the Energy Efficient Transport (EET) element, reference 2. The L-1011 was easily adapted to wing load alleviation because its outboard aileron remained effective at high speeds and contained series servo provisions for implementing the control signals. A breadboard load alleviation system was already under test on the full-scale L-1011 Vehicle Systems Simulator (VSS) at Lockheed's Rye Canyon research facility when the joint NASA/Lockheed program began. This program envisages flight verification of the load alleviation system on the baseline L-1011 aircraft and on the airplane with extended span augmented-stability control laws development using moving-base piloted simulation. Both the baseline load alleviation flight tests and the piloted simulated work have been completed successfully. This paper is to present and discuss selected results from these two tasks and it emphasizes the technology involved in their application.

SYMBOLS AND ACRONYMS

ACEE	Aircraft Energy Efficiency
ACS, ACT	Active Control System, Active Control Technology
AS	Augmented Stability
BL	Butt Line
C*	Normalized airplane response time history, $C^* = N_Z + 400q/g$.
CG, c.g.	Center of gravity

SYMBOLS AND ACRONYMS (Cont'd)

EET	Energy Efficient Transport
EHV	Electrohydraulic Valve
EMS	Elastic Mode Suppression
f	Frequency, Hz
FAR	Federal Air Regulations
G,g	Gravity, Damping
GA	Gust (load) Alleviation
GFAM	Graphics Flutter Analysis Method
KEAS	Knots Equivalent Airspeed
M	Mach Number
M_x, M_y	Bending Moment, Torsion Moment
MAC	Mean Aerodynamic Chord
MLC	Maneuver Load Control
n_z	Normal Load Factor
q	Pitch Rate, radians/sec
RE	Reduced Energy
RMS	Root Mean Square
SAS	Stability Augmentation System
V, Vg	Velocity, Gust Velocity
VFS	Visual Flight Simulator
VSS	Vehicle Systems Simulator
δa	Aileron Deflection
ζ	Fraction of Critical Damping
ωd, ωn	Damped and Undamped Natural Frequencies, radians/sec

WING LOAD ALLEVIATION

Basic Criteria

The basic criterion for the use of active controls in commercial transports is:

No Degradation of Safety

A second criterion required for airline schedule reliability is that the system be:

Non-dispatch Critical With One Channel Inoperative

The safety criterion is satisfied by the approach taken in the L-1011 yaw damper design, as illustrated in figure 1, and described more fully in Reference 3. Here the design limit gust load, associated with one occurrence in a 50,000-hour aircraft life, could be reduced from the level F in the figure to the level G - a one-third reduction, in this case - by installing a totally reliable yaw damper. If an extremely conservative assumption were made that the yaw damper was inoperative 3 percent of the time, then the design load would be at the level H, representing the combined probabilities E associated with a 97-percent operative, 3-percent inoperative yaw damper. This conservative design load level H is only slightly higher than the best level G and represents an attractive (approximately one-quarter) reduction from the no-active control (no yaw damper) value F.

From this illustration it may be seen that significant reduction in design loads and structure weight may be obtained with "state-of-the-art" active controls, that is, controls that may be inactive part of the time.

The second criterion, that the aircraft can be dispatched with one channel inoperative, sets the degree of system redundancy. This was selected for the L-1011 yaw damper as a "dual-dual" computer system with triple sensors, figure 2. See also reference 4. This same "dual-dual" system selection has been made for future in-service versions of the L-1011 wing load alleviation and stability augmentation systems.

It is of note that L-1011 service experience shows that the yaw damper has been inactive only about one hour per 100,000 flight hours. This record is three orders of magnitude better than the original design assumption. It suggests that later designs will assume a lower than 3 percent fraction of inoperative time.

System Description

The L-1011 is a triple-turbofan wide body commercial transport having the relatively high fuel efficiency and low noise of the high-bypass-ratio fan engine. An L-1011-500RE (RE for Reduced Energy) configuration is shown in figure 3, where the tip extensions and small tail (relative to the standard L-1011-1) are shown cross-hatched. The augmented-stability work was done with this configuration. The baseline active load alleviation flight tests were done with the standard L-1011-1 having a 2.74m (9 ft) shorter wing span and larger tail plus a longer fuselage than the -500. Its aspect ratio of 6.95 was proportioned for minimum direct operating costs when fuel was about 15 cents per gallon. The L-1011's relatively low design stress, wide-tread gear and outboard engine location all led to a relatively stiff wing in both bending and torsion, with the result that the outboard ailerons remain effective to the maximum design speed. This characteristic permits use of active wing load alleviation with only minor structural modifications which in turn permits the increased span and aspect ratio appropriate to a design optimized at a higher fuel cost level.

Roll control in the cruise configuration is by means of irreversible inboard and outboard ailerons, each with multiple actuators powered by multiple hydraulic systems. Spoilers add to the roll control in the flaps-down condition. The outboard ailerons of the test airplane, S/N 1001, contain series servos, found unnecessary for roll stabilization, which have been adapted to symmetric motion for active wing load alleviation. The L-1011 Vehicle Systems Simulator (VSS), a full-scale geometric duplication of the L-1011 control systems at Lockheed's Rye Canyon research facility, contains similar aileron series servos.

L-1011 pitch control is by means of a powered stabilizer with geared elevator, the gear ratio varying from zero at high-speed stabilizer angles, to about 3 at low-speed, flaps-down stabilizer angles. The stabilizer is powered by two left-hand and two right-hand actuators, supplied by four different hydraulic systems. An electrohydraulic series servo has been inserted into the series trim linkage to provide active control to the stabilizer. This system is also duplicated on the VSS.

A block diagram of the primary channel of the breadboard active control system (ACS) is shown in figure 4. The secondary channel required to assure fail-passive characteristics is identical except that the stabilizer series servo is not duplicated (the aileron series servos have dual windings). The aileron systems are cross monitored by comparison of corresponding left wing and right wing coil signals, whereas the stabilizer series servo has in-line monitoring by comparison with the output of an analog model of the series servo. In case of excessive signal difference the monitor logic shuts both channels down, and the series servos return to neutral, i.e., they fail passively. The production system will have two dual computer/monitor channels, providing a fail-operational, fail passive sequence.

Inasmuch as the ACS sensors provide currents proportional to acceleration or pitch rate, ground test is performed by inserting calibrated currents to the system. This is called "torquing" the system. Normal operation is checked by torquing both channels equally, and monitor operation by torquing only one channel.

It may be noted that, after initial "burn-in" in the laboratory, the system performed within specification and without any delays during the approximately 150 hours of laboratory and 60 hours of flight tests.

The load alleviation functions provided by the active controls are

Function	Surface	Sensors
Maneuver Load Control (MLC)	Outboard aileron	Wing-tip and body accelerometers
Elastic Mode Suppression (EMS)	Outboard aileron	Wing-tip and body accelerometers
Gust Alleviation (GA)	Stabilizer	Body pitch rate gyros and accelerometers

The maneuver load control is selected at a steady-state value of 8.7 deg/g to offset added bending moments from the extended tips at limit load factor, whereas the elastic mode suppression is chosen to damp the fundamental wing bending mode in the frequency range from 1.2 Hz to 2 Hz. This EMS function is as important as the MLC in controlling loads in turbulence, inasmuch as the wing load power spectrum shows peak contents at low frequency (short period longitudinal mode) and at the wing first bending frequency.

The stabilizer control is used both to offset trim changes due to the symmetric aileron deflections and to reduce airplane pitch response to gusts.

Referring again to the system block diagram shown in figure 4, the body and wingtip accelerometers are oppositely speed-scheduled so as to hold a constant MLC gain and a decreasing EMS gain with increasing airspeed. This scheduling helps to control both gain and phase angles to reduce sensitivity to higher-frequency wing (and fuselage) modes, and was selected in accordance with a design approach that emphasized the importance of flutter- and gust-related interactions with the active controls.

Loads Analysis Techniques

Active controls require an interdisciplinary approach, involving aerodynamics, handling qualities, loads, dynamics and controls expertise. The initial emphasis is on the aerodynamics/handling qualities/loads interactions to define the allowable configuration changes (e.g., extended span, smaller tail) that can lead to performance gains. Where load alleviation is required, the emphasis then shifts to loads/dynamics/controls expertise. Here it has become apparent that the primary responsibility for defining the control laws lies in the loads/dynamics area, in consultation with the avionics and mechanical controls experts. This fact is noted as a departure from past autopilot experience, where the prime responsibility lay with the avionics/controls experts.

The interdisciplinary approach is illustrated in the program flow diagram, figure 5. The tools used in the control law synthesis were

Maneuver Loads Program

Production Design Gust Loads Program

Production Flutter Programs on Computer Graphics

Flutter Optimization Programs

State-Space Models

Optimal Control Programs

Method of Constraints

The first three programs were the primary tools. A brief description of the programs and their uses follows:

Maneuver Loads Program - This is the existing set of L-1011 static aeroelastic loads programs. These programs use analytical representations of aerodynamics, mass (each 251 grid points per side) and stiffness (156 grid points per side) characteristics to perform closed form solutions for the aeroelastic loads at 251 grid points per side. They are updated to reflect measured stiffnesses, aerodynamic load distributions and weights.

Production Design Gust Loads Program - This program, used to determine design gust loads due to vertical gusts, includes analytical representation of two rigid-body modes plus 20 elastic modes and uses unsteady kernel function aerodynamics. A loads analysis of the elastic airplane is performed giving transfer functions, power spectral densities, rms loads for unit rms gust velocity, correlation coefficients, and frequency of exceedance for load quantities over the entire airplane. The program reflects flight test, ground vibration and wind tunnel test results.

Production Flutter Programs on Computer Graphics - An interactive computer graphics system, Graphics Flutter Analysis Methods (GFAM), reference 5, was developed by Lockheed-California Company to complement Lockheed's matrix oriented batch computing system. GFAM is utilized when the problem requires rapid analysis with a high degree of interaction between the engineer and computer. The GFAM L-1011 ACT Synthesis/Flutter Model is a 117 structural degrees of freedom simple beam element representation using unsteady kernel function aerodynamics adjusted for wind tunnel (steady) data. The generalized coordinates include 3 airplane rigid body, one free pitch stabilizer, 35 full airplane vibration modes, 5 simply supported stabilizer modes and 6 unit modes which are associated with the aileron and stabilizer attachment points degrees of freedom.

Program FLUTTER in GFAM computes V-f-g data and plots the data against a reference case which may have been generated in batch. Program FLUTTER VEL. computes the flutter velocity directly.

Flutter Optimization Program - Structural resizing for flutter occurs in two parts. First, the initial structural resizing to satisfy all flutter requirements. Second, the resizing for minimum weight while explicitly satisfying flutter requirements and not violating strength requirements. The engineer performs both resizings in GFAM.

Method of Constraints - Closed loop constraint gain-phase data for each of the flutter and dynamic gust requirements are computed in GFAM using programs FLUTTER FEED and GUST FEED for flutter and gust requirements. From the gain-phase constraint computations, data that best satisfy the objectives of the study are derived. The control law that best fits the constraint gain-phase data is derived with the additional input of realistic mechanization of hardware constraints using program BODE in GFAM. Finally, the closed loop analysis for flutter is performed in GFAM to verify the objectives of the analysis.

State-Space Models - A 40 X 40 state-space (time domain) airplane model was generated in order to perform a quadratic optimization. The model contained 2 rigid and 6 elastic modes, stabilizer control dynamics and unsteady aerodynamics in the time domain based on least square fits of kernel function aerodynamics at selected frequencies. The model was sufficiently accurate to predict handling qualities and loads but insufficient to predict certain flutter modes. A reduced version of the 40 X 40 (i.e., a 12 X 12) state-space model was used to conduct laboratory simulation tests.

Optimal Control Programs - The state-space quadratic optimization procedure utilizes a synthesis algorithm which defines a direct matrix algebra solution of optimal feedback gains. A problem area associated with this application was the excessive number of feedback gains obtained from the full state feedback solution. Current independently funded research is underway to solve the partial state feedback problem.

Alleviation System Tests

The active controls computer was assembled, burned-in and functionally tested in Lockheed's Rye Canyon research facility as described in Reference 6, using the L-1011 Vehicle Systems Simulator (VSS) and Visual Flight Simulator (VFS). The VSS, a full-scale geometrically similar layout of the L-1011 systems, included duplicate series servos, aileron and stabilizer control systems, and L-1011 cockpit controls. Simulated flight was performed by closing the aircraft loop through the VFS. This loop was simulated by a 12 X 12 state space equations set that included three elastic modes. Although the VSS/VFS test results will not be discussed in this paper, it should be noted that these tests developed the final flight test configuration and the pre-flight test system, as well as verifying the specification performance of the active systems. They were a necessary and valuable prerequisite to the flight testing.

The flight tests consisted of:

1. Flutter-type tests to assure that the active controls did not produce any instabilities or noticeable reductions in damping at gains up to twice nominal. These tests were carried to near the limit design speed V_D and Mach number M_D and showed no deterioration in damping even at twice nominal gain.

2. Open- and closed-loop transfer function tests. The open-loop tests, covering response to sinusoidal excitations of the symmetric outboard ailerons and stabilizer separately, checked the analytical description of the airplane and the aerodynamic forces. The excitations covered the range from 0.1 Hz (low speed) or 0.3 Hz (high speed) to about 3 Hz. The speeds ranged from 145 KEAS, flaps down, Mach 0.26, to 378 KEAS, Mach 0.88. Low and high wing fuels were tested. Closed-loop tests checking the performance of the active systems were performed by turning the active systems ON during the sinusoidal excitation. These closed-loop checks were made for 145 KEAS, 345 KEAS and 378 KEAS (Mach numbers 0.26, 0.80 and 0.88, respectively).

3. Maneuver Loads Tests. These consisted of wind-up turns to 1.8 g load factor and push-downs and pull-ups. In addition, the symmetric aileron effectiveness was checked in level flight at 345 KEAS by inserting steady electric signals to hold the outboard ailerons at 5 different steady positions.

4. Gust Loads Tests. With a gust boom installed, gust loads tests were performed at low speed, flaps down, and at cruise speed. Good data were obtained at cruise speed, but the low-speed data were not adequate for meaningful analysis.

Load Alleviation Results and Discussion

Transfer Function Tests - Open-loop transfer function test results and comparisons with predictions for both amplitude and phase, are shown in figures 6 through 12. They represent motions of the wing tips, engine, pilot seat and stabilizer tips, drives by aileron and stabilizer, and speeds of 145 KEAS and 345 KEAS. In all cases the agreement between test and predicted results varied from good to remarkable. These motion predictions were made using the same Graphics Flutter Analysis Methods (GFAM) interactive flutter program that was used for specifying control law phasing. The excellent agreement indicates that the data base and the adequacy of the mathematical description are excellent.

Open-loop loads transfer functions are compared with VGA program predictions in figures 13 through 18. Good test/analysis agreement is shown except that the stabilizer loads were somewhat higher than predicted.

The effects on wing-tip accelerations of closing the loop are shown in figures 19 through 21. They show that the active controls damp the wing bending mode at about 1.6 Hz and have little effect on the higher frequency modes; two engine modes at 2.2 Hz and 2.7 Hz, and fuselage and stabilizer bending modes at 3.5 Hz and 5 Hz.

The wing bending load effects of the active controls are shown in figure 22 for a station at 52 percent semispan. The bending moment at low frequency, 0.3 Hz, was reduced 50 percent, and the wing bending peak at 1.6 Hz was reduced in a manner similar to the wing-tip accelerations at this frequency.

Overall, the transfer function test results confirmed both the mathematical modeling of the airplane and the effectiveness of the active controls.

Maneuver Loads Tests - Typical results for the variation with load factor of wing bending moment, shear and torsion at wing BL 702 (75% semispan) are shown in figures 23 to 25 for the 345-KEAS cruise condition. The bending moments and shears were reduced by the active controls, and the torsion loads were increased, all approximately as predicted.

The symmetric aileron effectiveness per degree is summarized in figure 26, where the incremental bending moment is related to the 1-g bending moment at each span position. The test data, although scattered, give reasonable confirmation to the pre-flight predictions.

Gust Response - The gust response test/analysis correlation was still in process as this paper was being prepared. Some test data were available, however, to show the effect of the active controls. Figure 27 shows cross-spectrum transfer functions of wing bending at BL 286 (31 percent semispan) relative to the measured gust velocity. The solid curve is sight-averaged from overlay plots of the two available ACS-on test runs, and the dashed curve is sight-averaged from overlay plots of the two available ACS-off runs. It may be seen that the active systems provide a substantial wing load reduction in the frequency range below 2 Hz.

STABILITY AUGMENTATION

Criteria

The approach to developing an augmentation system for the small-tail L-1011 active controls derivative airplane was to use the current L-1011 in the manual control mode as the standard of acceptable performance. The small-tail configuration with augmented stability (L-1011-500 RE) was designed such that handling qualities are at least as good as those of the current L-1011. In order to assure this, the following specific criteria were selected.

1. Normalized C* and pitch rate time history response will lie within the envelope of these parameters for the current L-1011. C* is a weighted sum of normal acceleration and pitch rate, $C^* = n_z + 400q/g$

2. Frequency response criteria will assure that oscillatory characteristics compare favorably with current transports.

3. There will be no roots with time to double amplitude less than 55 seconds.

4. There will be at least one pound column force for each six knots speed change away from trim as required by the Federal Aviation Regulations.

The normalized C* step input response time history envelope of the current L-1011 for a wide range of weight and c.g. conditions at a typical cruise flight condition is shown on figure 28. The dotted lines indicate the upper and lower boundaries of this envelope used as a criterion. Figure 29 includes the root locus for the unaugmented current airplane with the big tail as the oscillatory chacteristics which were objectives in the augmentation system.

System Description

The L-1011-500 RE is depicted in figure 3 with the small horizontal tail shown shaded. The small tail has approximately 60% as much exposed area as the current big tail shown in dashed outline. Considering the destabilizing effect of the small tail and stabilizing effect of the extended wing tips, the net inherent stability loss for the L-1011-500 RE compared to the current L-1011 is 5% static margin at low speed conditions and, in cruise, about 3% at M = 0.80 decreasing to no loss at M = 0.90 and above. Corresponding neutral point locations with the small tail are approximately 42% MAC for the landing approach configuration and 38% to 41% MAC in cruise. Comparable L-1011 values are 47% on landing approach and 41.5% MAC in cruise. Ground balance requirements about the main landing gear dictate an L-1011 operational aft c.g. limit of 35% MAC for takeoff and landing, although in-flight c.g. locations aft of this limit are possible for research purposes. Retaining this aft limit for the L-1011-500RE gives the small-tail airplane a static margin varying from 3% to 7% MAC depending on flight conditions.

The design of the augmentation system was based on consideration of the following characteristics of the unaugmented small-tail airplane with the c.g. at the operational aft limit.

1. Results from the piloted flight simulation show generally acceptable handling qualities.

2. Normalized time history characteristics are within selected criteria boundaries.

3. The undamped angular frequency characteristics are considered unacceptably low.

Based on these findings it was concluded that good handling qualities could be achieved with a simple augmentation system which would be highly reliable. This system identified herein as System 1 was conceived as a lagged pitch rate damper to provide the necessary short-period frequency and damping characteristics to suppress turbulence effects. In addition, a washed-out column feed-forward loop was designed to provide the flexibility of adjusting the C* and pitch rate time history characteristics without affecting stability. This loop was used to increase pitch response to control input as in System 2 or to decrease it as in System 3.

The current L-1011 is equipped with Mach trim compensation to give a satisfactory stable stick force gradient with velocity at high speed to comply with FAR part 25 requirements. In this study a new Mach trim system has been defined for the small-tail airplane and its characteristics have been incorporated into the basic airframe speed derivatives. The Avionics Flight Control System of the current L-1011 includes complete automatic pilot modes and it is assumed that a small-tail derivative would also possess this capability. However, no autopilot effects are included in this study although the autopilot would provide a dual channel backup for the pitch stability augmentation system.

Augmentation Design Analysis

Control system analysis was performed using a linearized aerodynamic model. Pitch rate time histories obtained with this model show close agreement with those from digital computer program solutions using the complete flight regime nonlinear aerodynamic simulation model.

Short-period frequency and damping values were sought for the augmented small-tail airplane which would equal or exceed those of the baseline airplane at 25% c.g. Figure 29 shows the effect of c.g. location on characteristic short-period roots of the small-tail L-1011-500RE with the lagged pitch rate damper, system 1, compared with the baseline airplane. These data show that the damping ratio (ζ) of the big-tail airplane is matched while frequency (ω) is increased. It is noteworthy that the augmented system significantly increases the frequency over that of the unaugmented small-tail airplane, and also because of pitch damper lag, suppresses the low frequency instability present for the unaugmented small-tail airplane at 40% c.g. in cruise.

Normalized C* step response time history characteristics of the small-tail L-1011-500 RE with the pitch damper (System 1) are shown as solid lines in figure 28. These data for cruise are well centered between the criteria boundaries. In order to evaluate the importance of C* in the flight simulation, the upper and lower boundaries are matched by activating the washed-out column feed forward loop. It was found that an upper boundary match was facilitated by reducing the pitch damper gain in addition to the column feed forward manipulation; this system is identified as System 2. A lower boundary match was achieved by slightly reducing the stabilizer to column gain; this is identified as System 3.

Because the purpose of this study is to investigate the effects of relaxed static stability, c.g. locations forward of 25% MAC were not included in the flight simulation and were therefore not considered at this stage of the augmentation system development.

Simulation Tests

Flight simulation was conducted on the Lockheed Rye Canyon 4DOF moving base Visual Flight Simulator. An L-1011 cab equipped with televised outside forward visual presentation and cockpit instrumentation including an L-1011 Flight Director was installed on the motion system. Continuous random turbulence of RMS levels up to 2.7m/sec (9 fps) on approach and 3.7m/sec (12 fps) in cruise was simulated using the Dryden spectral form (ref. 7).

Pilots were asked to perform typical flying tasks in varying levels of turbulence at several conditions of static stability. The cruise task consisted of making small altitude and heading changes at M = 0.83 at 10058m (33000 ft.) altitude. The approach task was started 16 km (10 miles) from the runway threshold at 457 m (1500 ft) altitude. Flaps, initially at 10°, were lowered to 26° and then to 33° as gear was extended. An instrument approach was flown using the flight director. Three pilots rated flying qualities using the Cooper-Harper rating scale (ref. 8). Their opinions are presented in composite form on figures 30 through 33.

Simulation Results and Discussion

Figure 30 presents the results of an evaluation of cruise flying qualities for the small-tail L-1011-500 RE with no stability augmentation. In this flight condition turbulence did not significantly affect controllability, but center of gravity location had a marked effect on altitude and pitch attitude control. Pilots commented that because of sluggish response and difficult attitude control, cruise flight at less than 5% MAC static margin with neither stability augmentation nor autopilot would be acceptable only for the brief time period necessary to achieve a more favorable flight condition.

Figure 31 shows comparable evaluation with the stability augmentation engaged. All pilots reported that the augmentation provided a significant improvement in controllability at aft centers of gravity in both levels of air turbulence. There is no clear-cut preference for one system over another, which suggests that the improvement in pitch damping provided by system 1 and present in all systems is more significant than differences in aircraft control response.

Results of an evaluation of approach flying qualities for the L-1011-500RE with no stability augmentation are given in Figure 32. Pilot ratings and comments indicate that aft movement of the c.g. does not appreciably degrade controllability of the small-tail configuration until the c.g. location exceeds 40% MAC. The effect of turbulence on the ratings, however, is pronounced at all c.g. locations, degrading the pilots' ability to control glideslope satisfactorily.

Figure 33 presents pilot ratings of landing approach flying qualities with augmentation. In calm air, because the unaugmented small-tail aircraft was relatively easy to fly, the rating improvement with augmentation was small. In heavy turbulence, a significant improvement was observed at all c.g. locations. The pilots were able to capture and track the glideslope with an acceptable level of work load.

As in the cruise condition, a comparison of the baseline to the L-1011-500RE with augmentation engaged shows the two configurations to be equivalent in calm air but the augmented small-tail L-1011-500 RE is easier to fly in heavy turbulence.

Statistical data showing the effects of air turbulence during cruise on the small-tail airplane with augmentation on and off are compared to the baseline level in figures 34 and 35. Figure 34 shows the effect of reduced tail size on load factor, pitch attitude and pitch rate. There is a slight reduction in normal load factor deviation for the small-tail configuration both with and without augmentation, but the greatest effects are on pitch rate, the feedback variable, and pitch attitude.

Figure 35 summarizes the relative effects of turbulence on primary control system parameters. The column motion required to control the aircraft is significantly less for the augmented small-tail airplane than for the same aircraft without augmentation. This trend is also apparent in the control force implying a reduction in work load. Stabilizer motion is greater for the small-tail aircraft because of the requirement to compensate for reduced inherent damping and control power either by increased pilot activity or by an automatic system. Considering only the small tail, the stabilizer motion is reduced by use of the augmentation system.

CONCLUSIONS

From baseline tests and analysis of an active load alleviation system on the L-1011, it is concluded that

1. Control laws derived using production (large-scale) loads, flutter and gust analysis programs provided satisfactory static and dynamic wing load alleviation without introducing new dynamic problems.

2. The available data base - mass, stiffness and aerodynamics of the L-1011 - built up from previous analyses plus ground, flight and wind-tunnel tests was entirely sufficient, in conjunction with the large-scale analysis programs, for deriving the control laws.

3. The results of the baseline tests and analyses have provided a good base for the next step, the use of active controls with extended tips.

From results of the aft-c.g. simulation study, it is concluded that

4. A simple, reliable pitch augmentation system will restore satisfactory flying qualities to neutrally stable commercial transport aircraft.

5. Flying qualities are generally acceptable for those aircraft with as little as 5% static margin in the event of complete failure of augmentation.

To generalize, it may be concluded that derivative aircraft, benefitting from good data bases and analytical techniques, can make immediate use of active controls for load alleviation and stability augmentation, to the extent of their control system capability.

REFERENCES

1. Povinelli, F. P., Klineberg, J. M., and Kramer, J. J.: Improving Aircraft Energy Efficiency. AIAA Astronautics and Aeronautics, pp. 18-31, February, 1976.

2. Leonard, R. W., and Wagner, R. D.: Airframe Technology for Energy Efficient Transport Aircraft. SAE 1976 Transactions, Section 4, pgs. 2916-2931, Sept. 23, 1977.

3. Hoblit, F. M.: Effect of Yaw Damper on Lateral Gust Loads in Design of the L-1011 Transport. Presented at 37th Meeting of the AGARD Structures and Materials Panel, The Hague, Netherlands, 7-12 October, 1973.

4. Flapper, J. A., and Throndsen, E. O.: L-1011 Flight Control System. AGARDograph AGARD-AG-224, April, 1977.

5. Radovcich, N. A.: Graphics Flutter Analysis Methods - An Interactive Computing System at Lockheed-California Company. Paper No. 8 of NASA SP-390. Presented at Langley Research Center, October 1-2, 1975.

6. Foss, R. L., and Lewolt, J. G.: Use of Active Controls for Fuel Conservation of Commercial Transports, AIAA Paper No. 77-1220, Presented at AIAA Aircraft Systems and Technology Meeting, Seattle, Wash., August 22-24, 1977.

7. MIL-F-8785-B; Military Specification, Flying Qualities of Piloted Airplanes.

8. Cooper, George E.; and Harper, Robert P. Jr.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

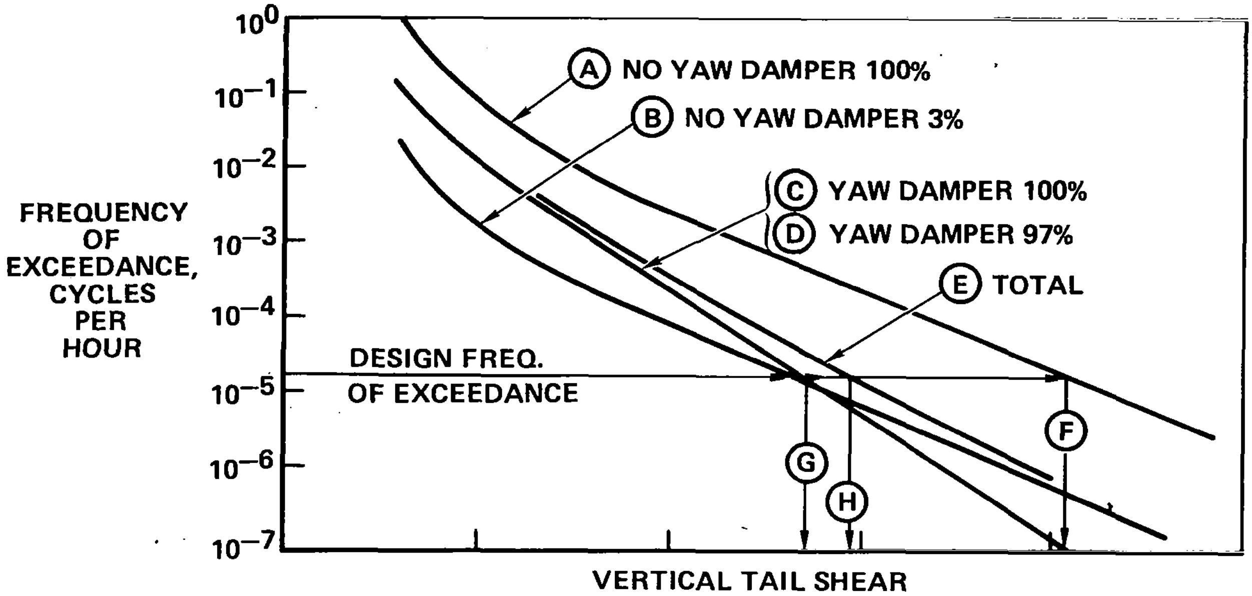


Figure 1.- Probability approach — gust loads.

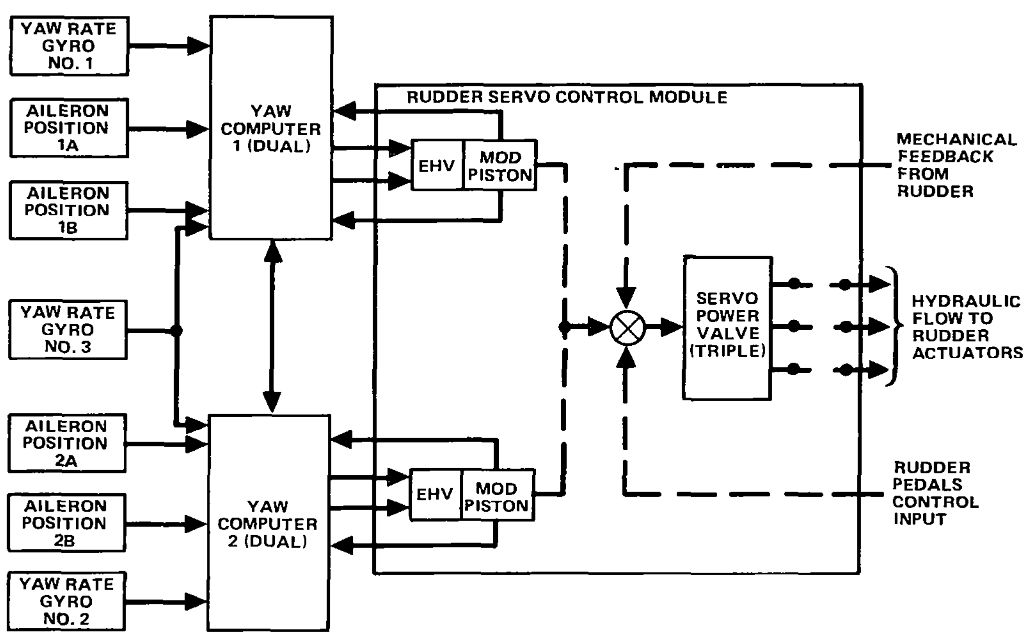


Figure 2.- L-1011 active YAWSAS.

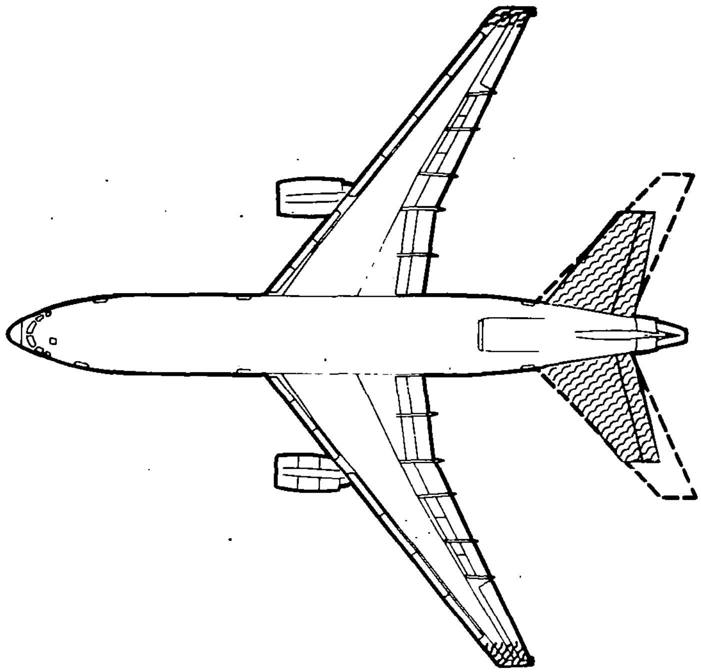


Figure 3.- L-1011-500 RE general arrangement.

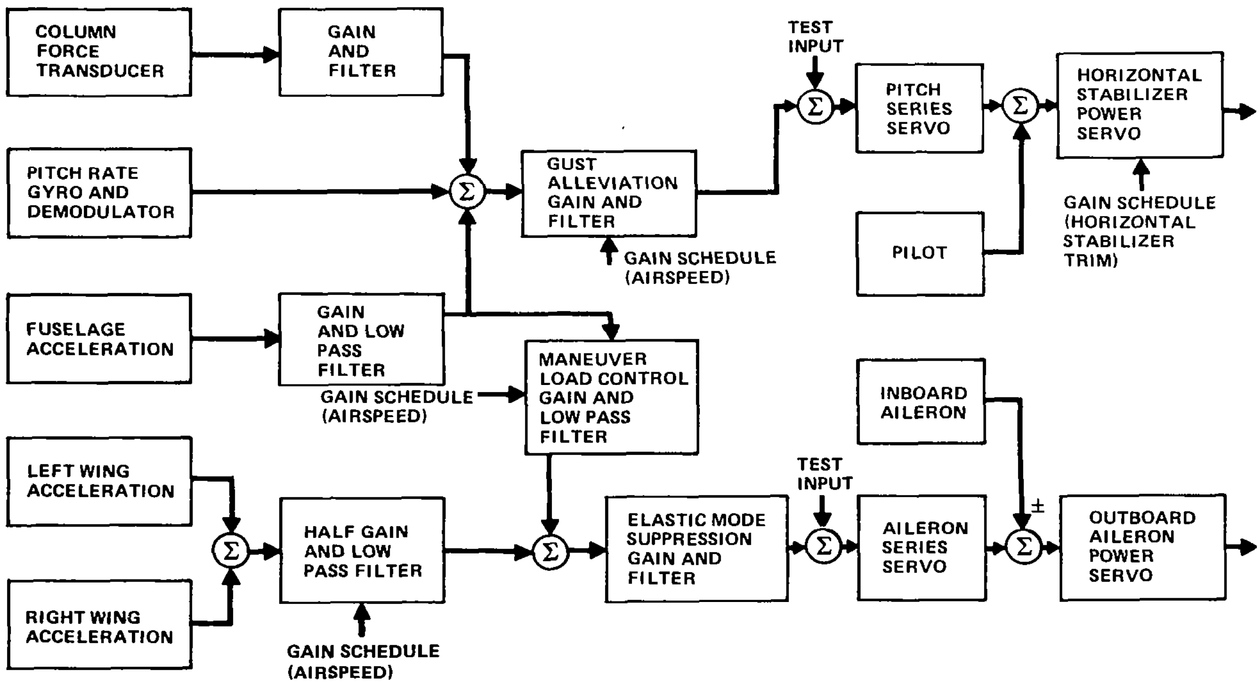


Figure 4.- L-1011 MLC/EMS/GA system block diagram.

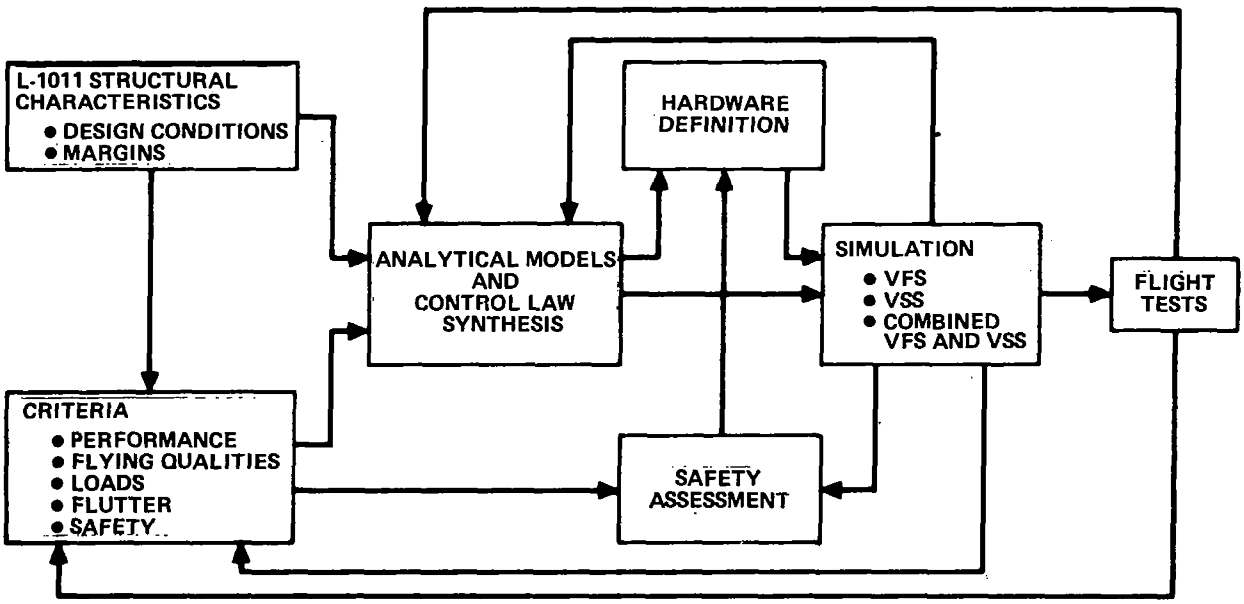
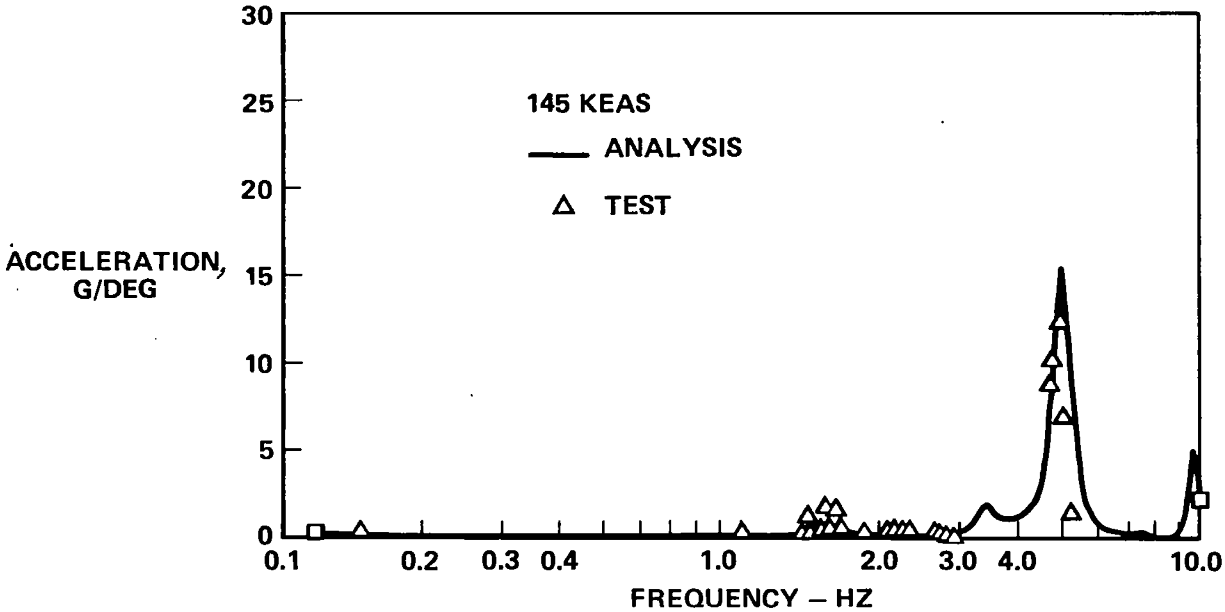
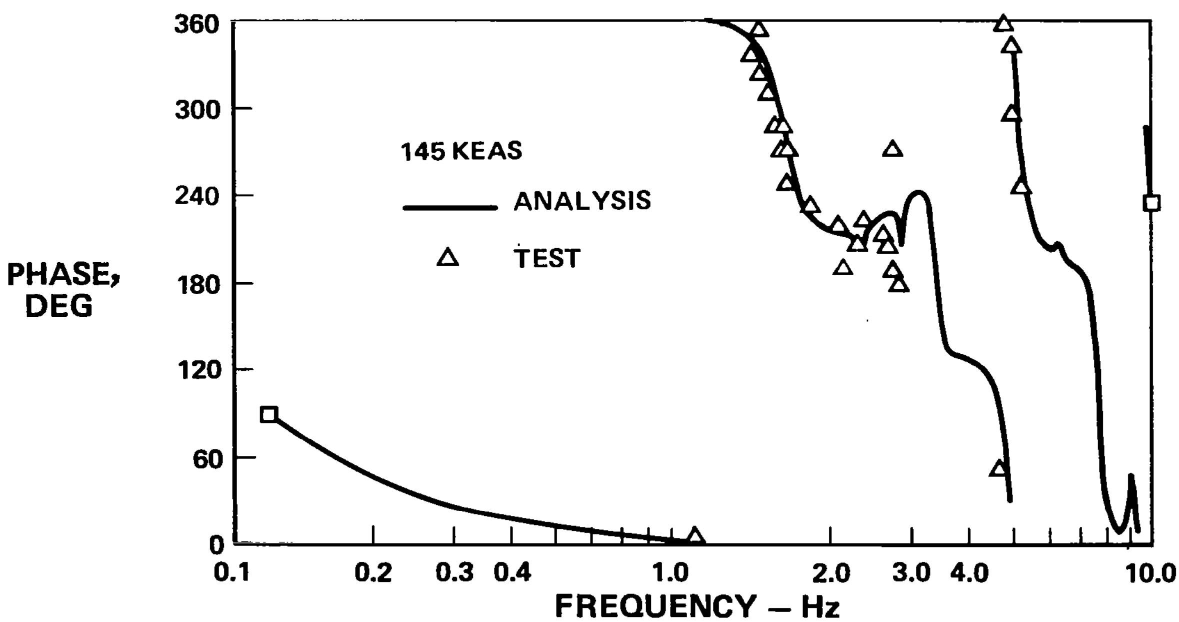


Figure 5.- Program flow diagram.

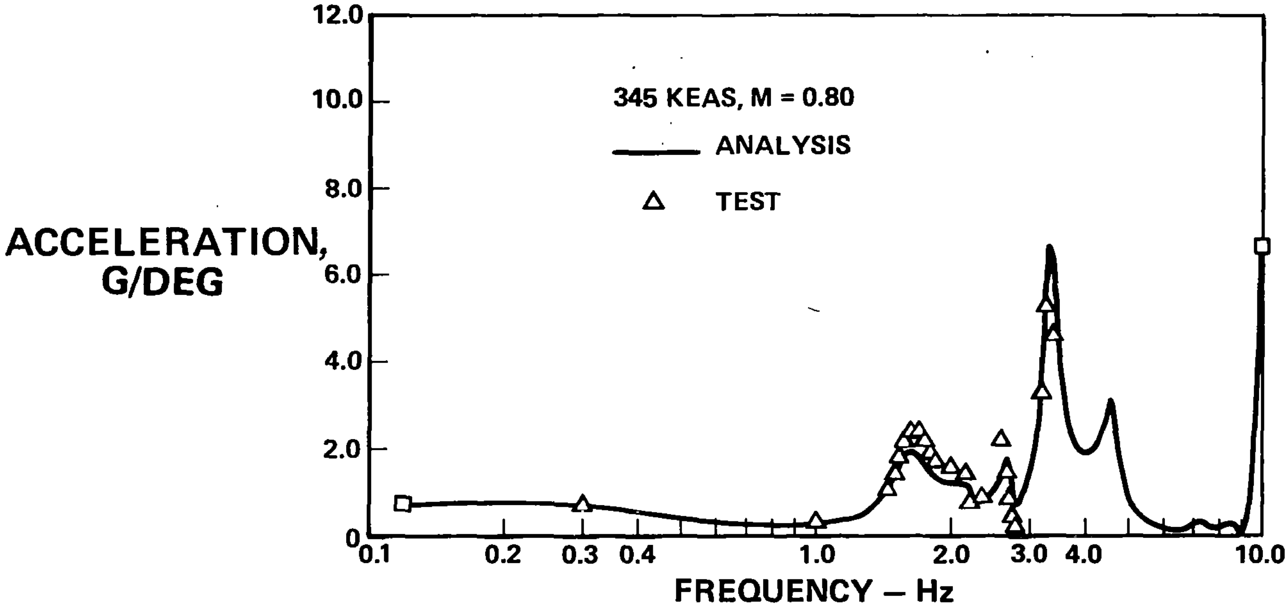


(a) Magnitude.

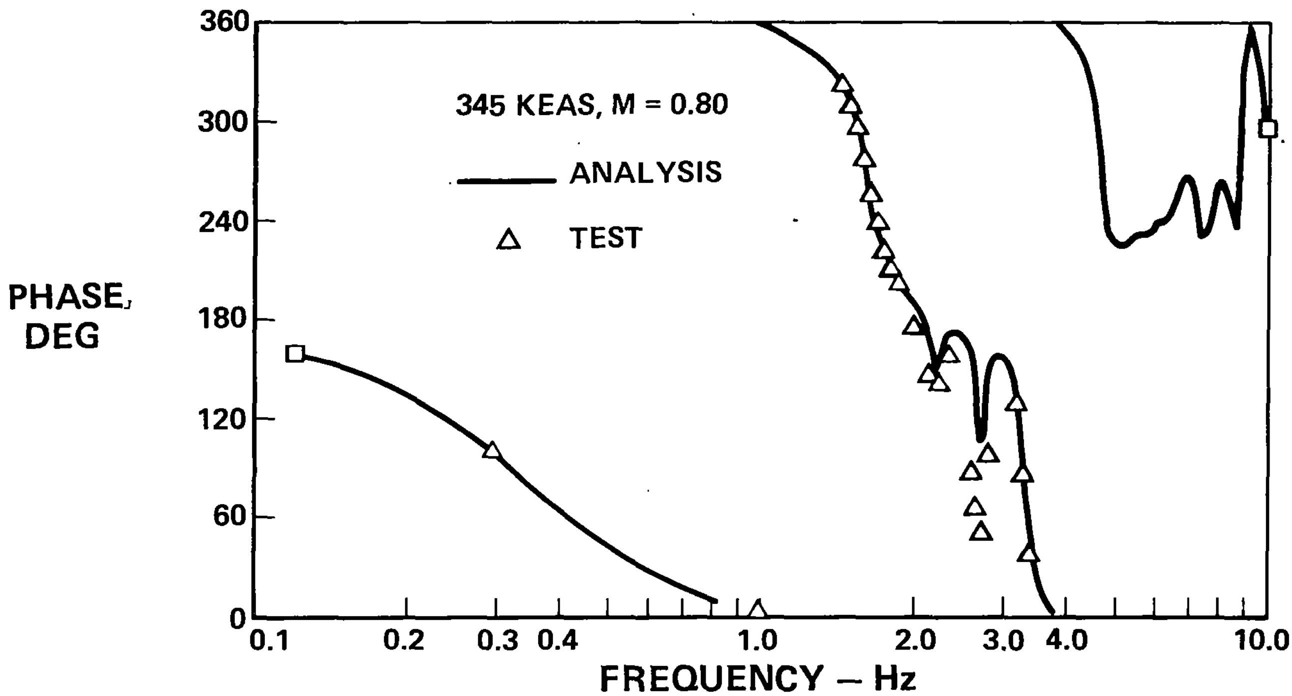


(b) Phase.

Figure 6.- Wing-tip acceleration — stabilizer drive ACS OFF.

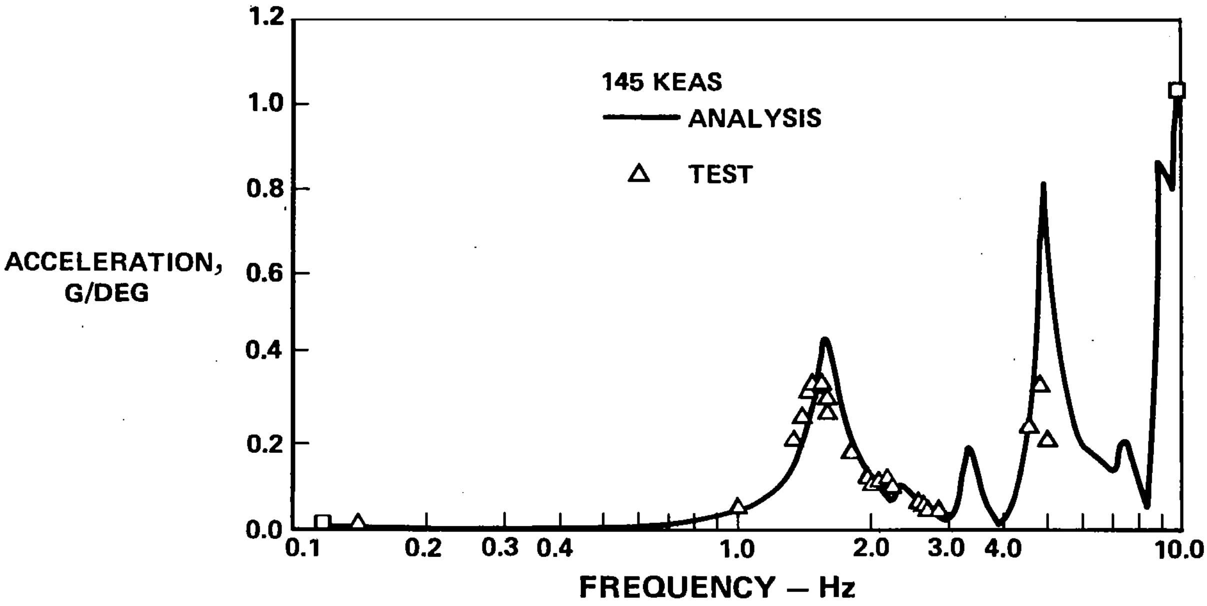


(a) Magnitude.

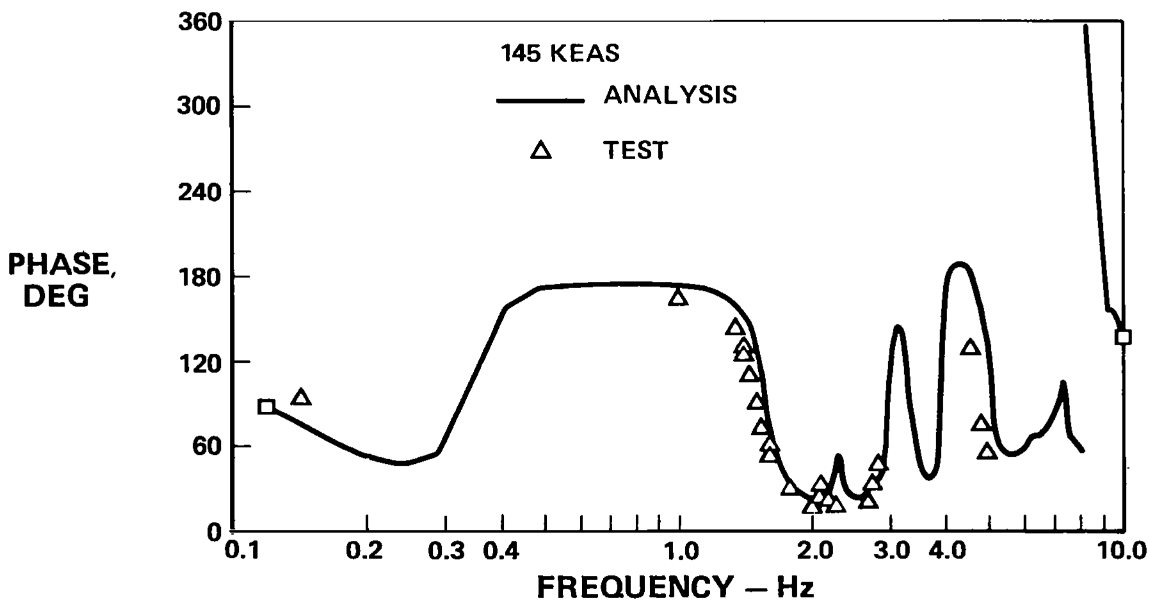


(b) Phase.

Figure 7.- Wing-tip acceleration — stabilizer drive ACS OFF.

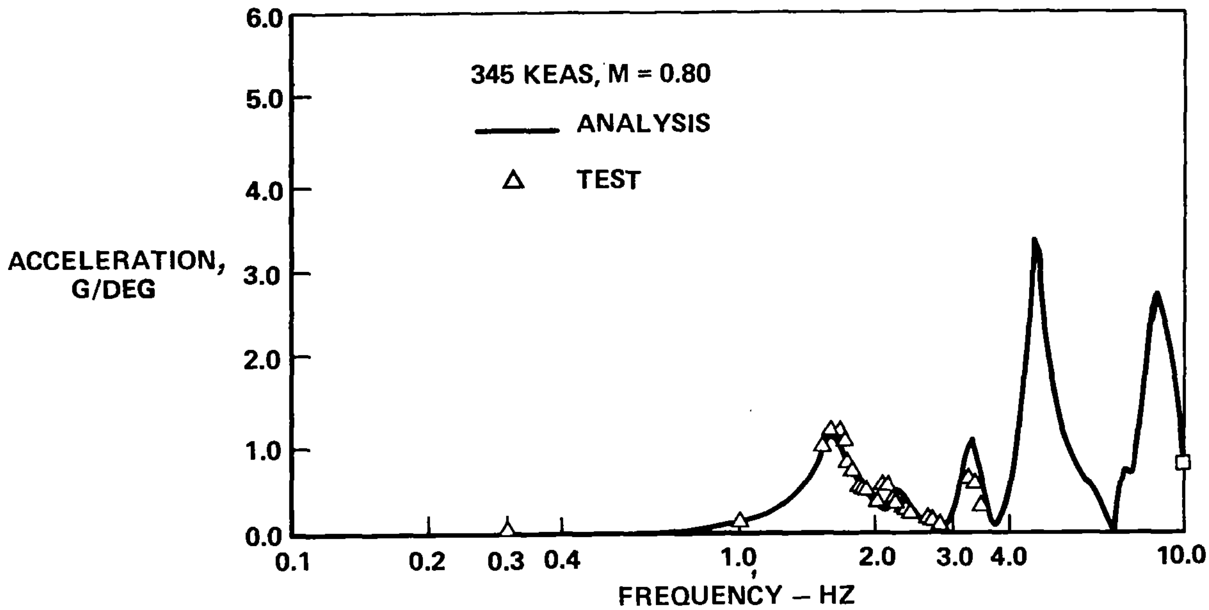


(a) Magnitude.

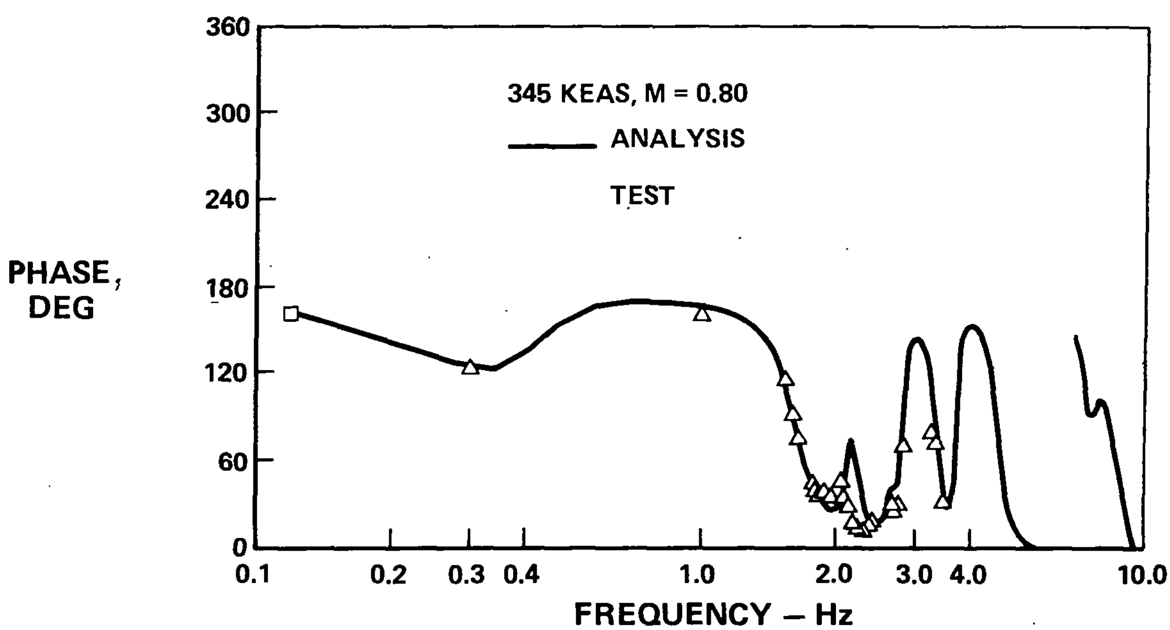


(b) Phase.

Figure 8.- Wing-tip acceleration — aileron drive ACS OFF.

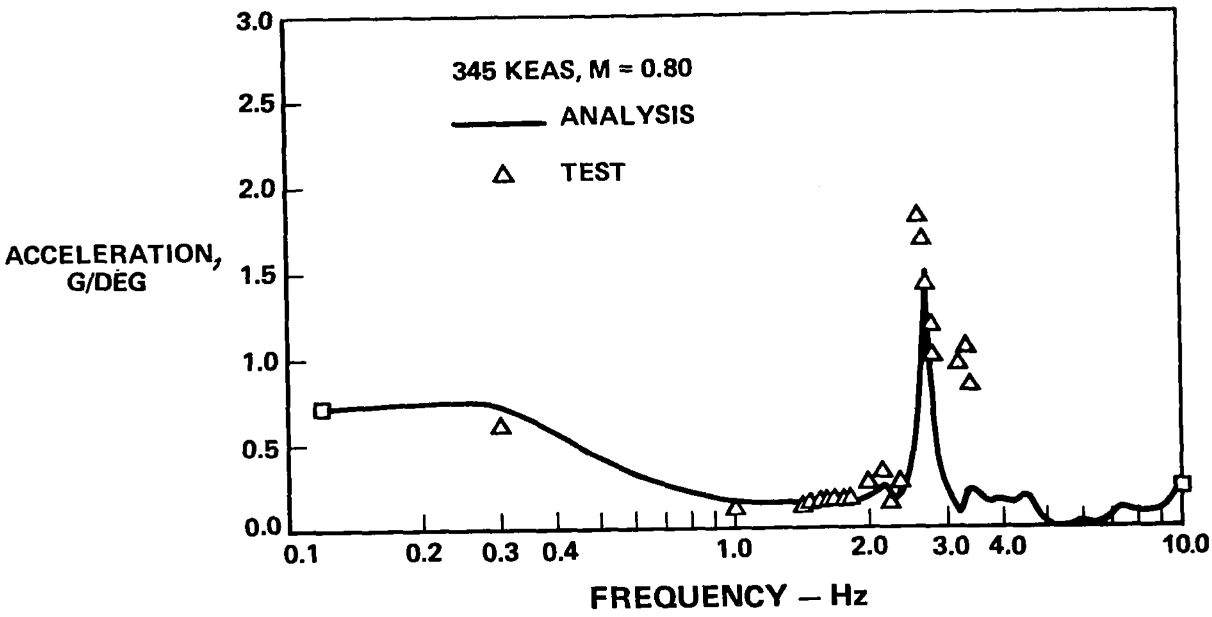


(a) Magnitude.

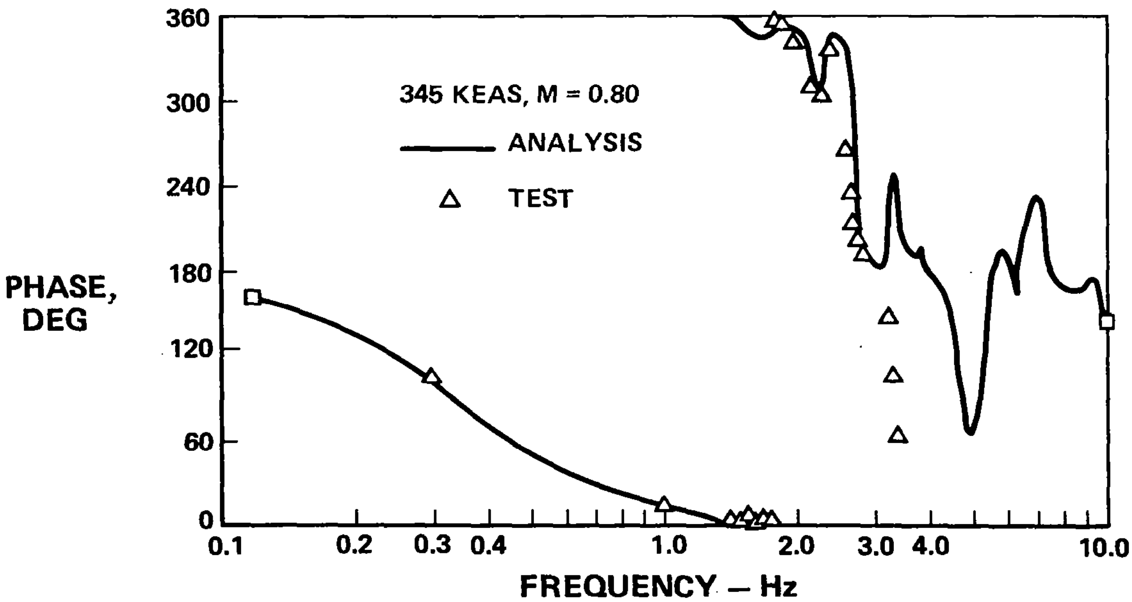


(b) Phase.

Figure 9.- Wing-tip acceleration — aileron drive ACS OFF.

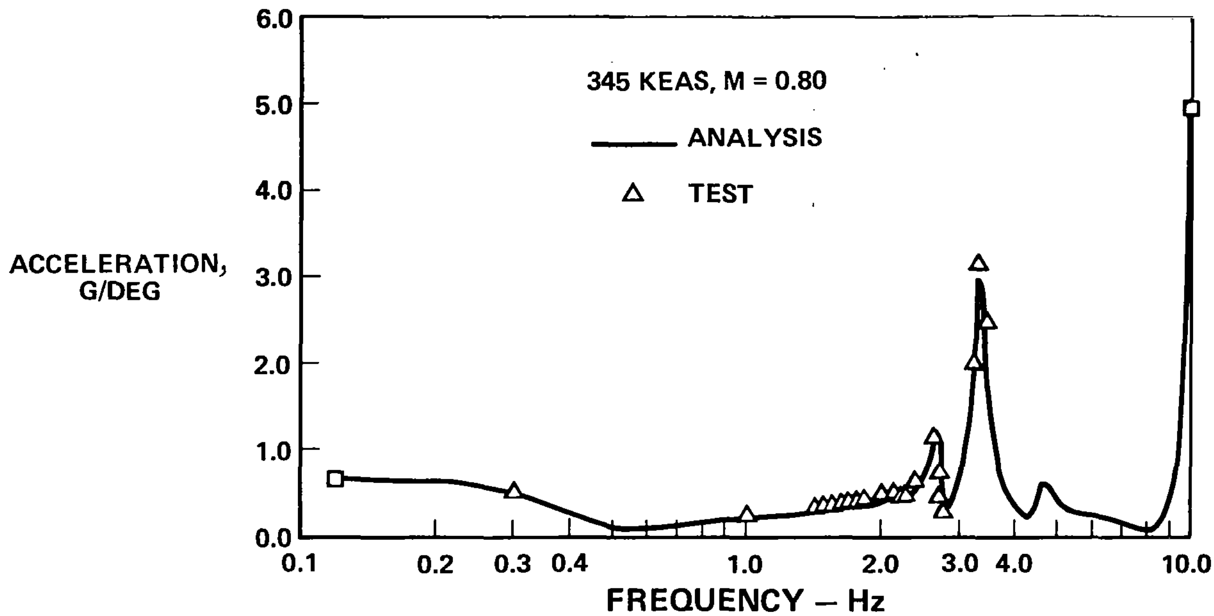


(a) Magnitude.

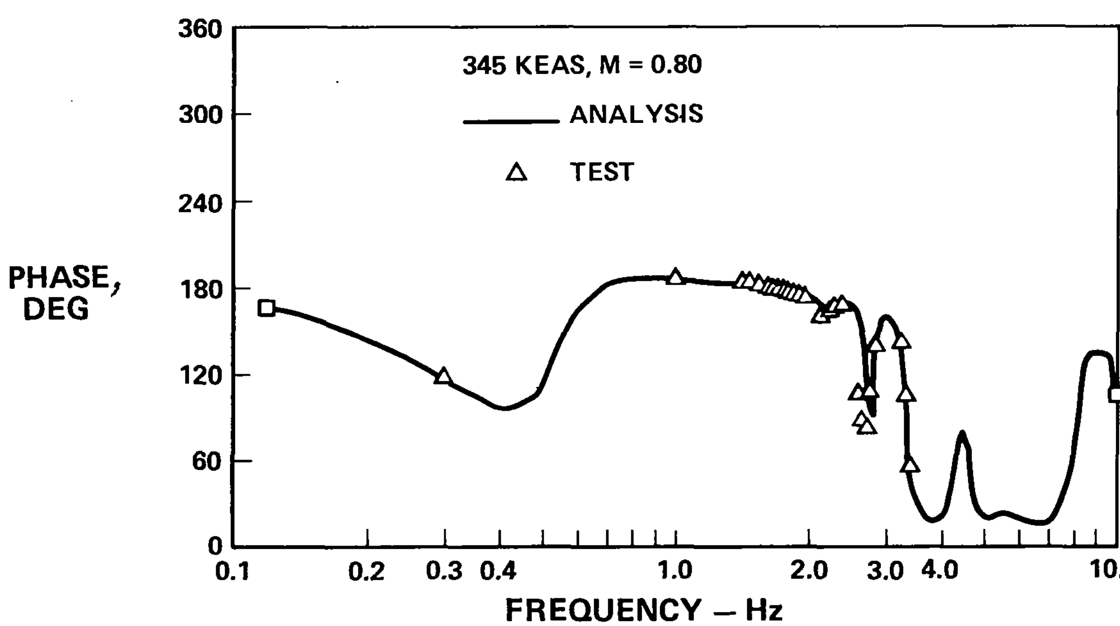


(b) Phase.

Figure 10.- Engine normal acceleration — stabilizer drive ACS OFF.

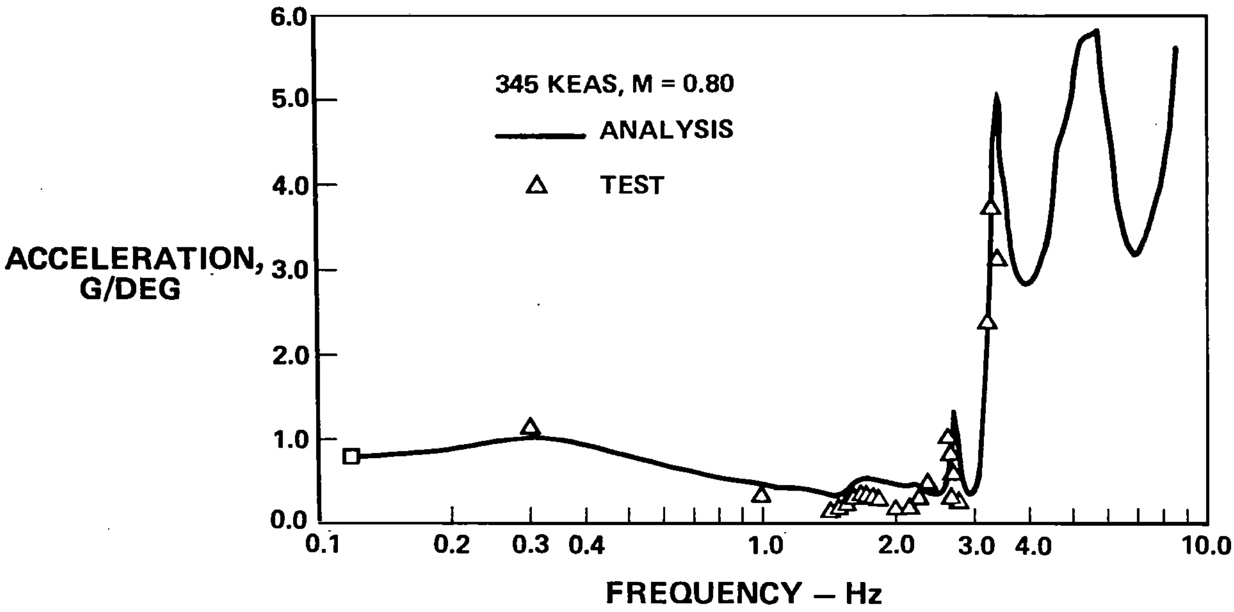


(a) Magnitude.

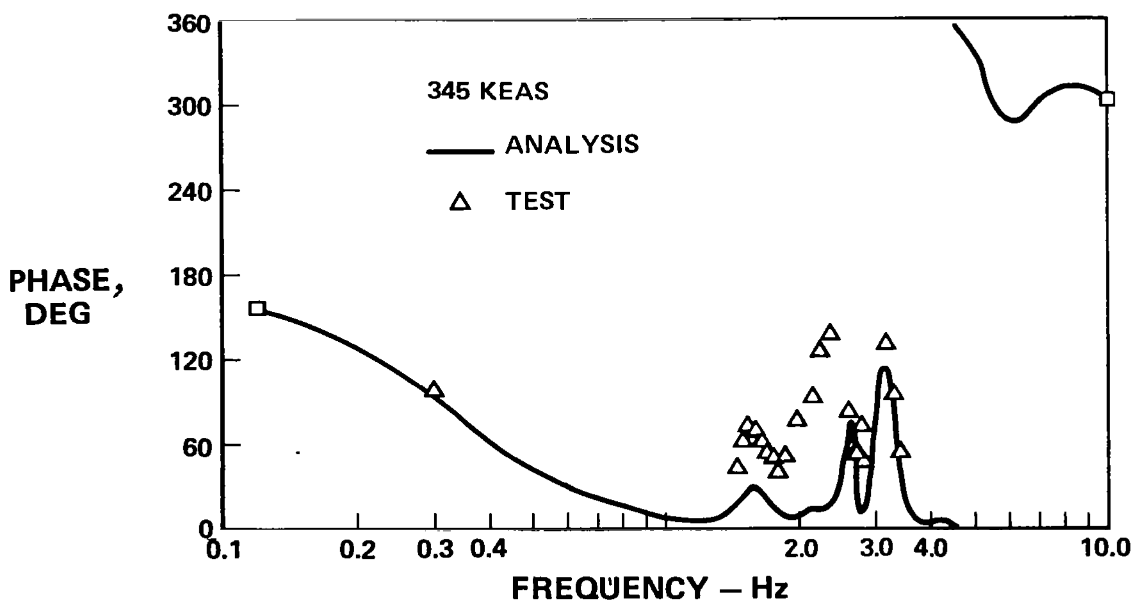


(b) Phase.

Figure 11.- Pilot acceleration — stabilizer drive ACS OFF.



(a) Magnitude.



(b) Phase.

Figure 12.- Stabilizer tip acceleration — stabilizer drive ACS OFF.

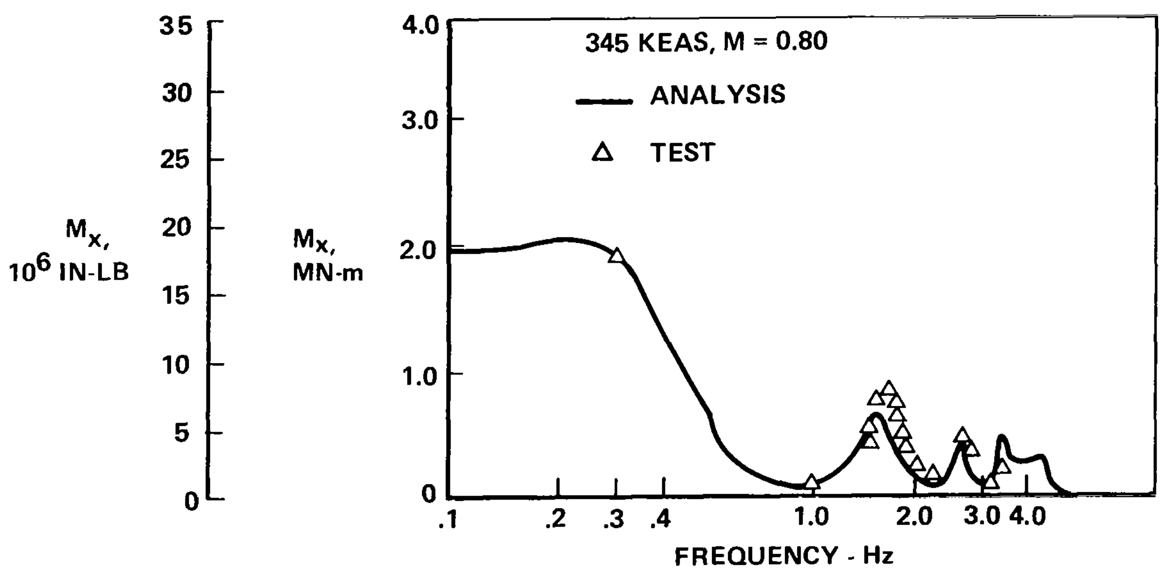


Figure 13.- Wing bending moment at BL 183/degree stabilizer.

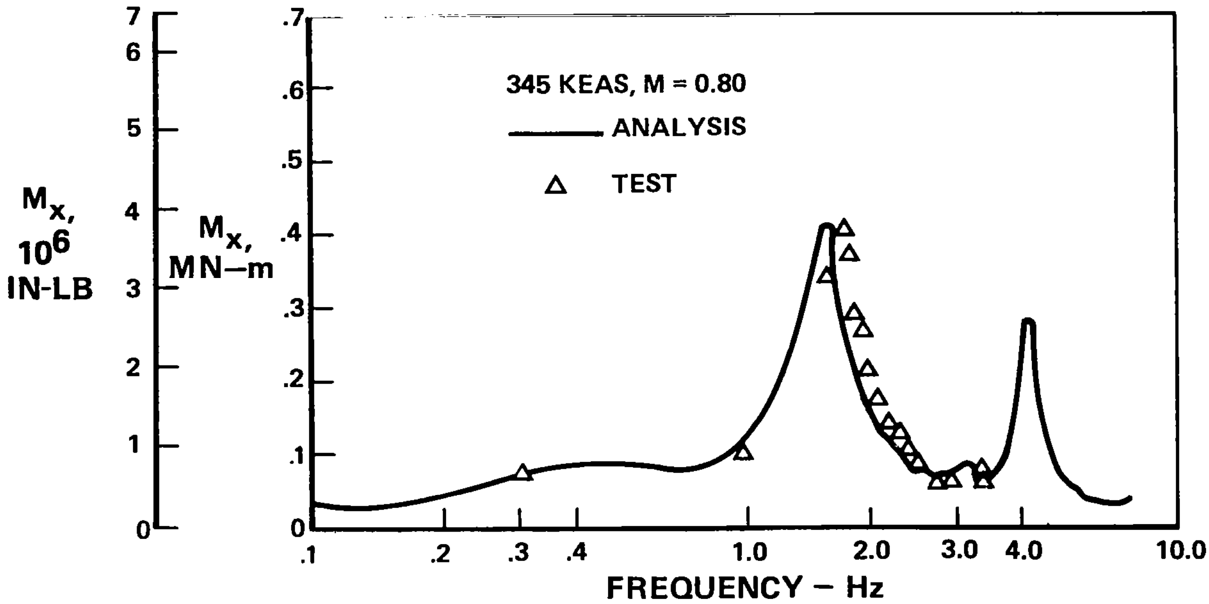


Figure 14.- Wing bending moment at BL 183/degree aileron.

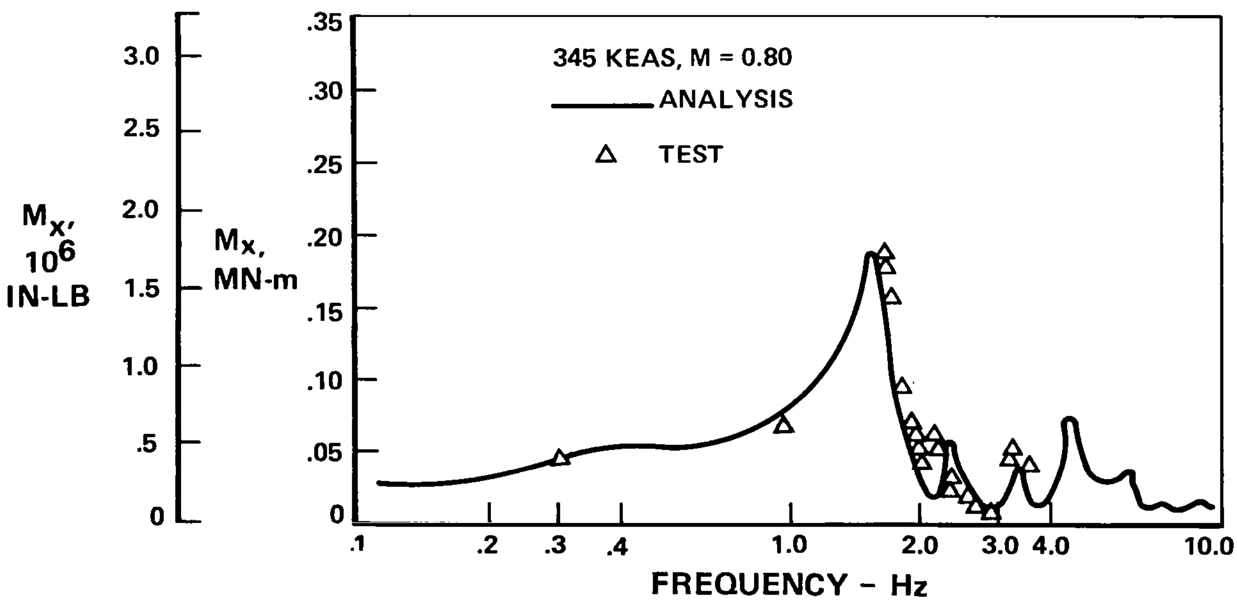


Figure 15.- Wing bending moment at BL 487/degree aileron.

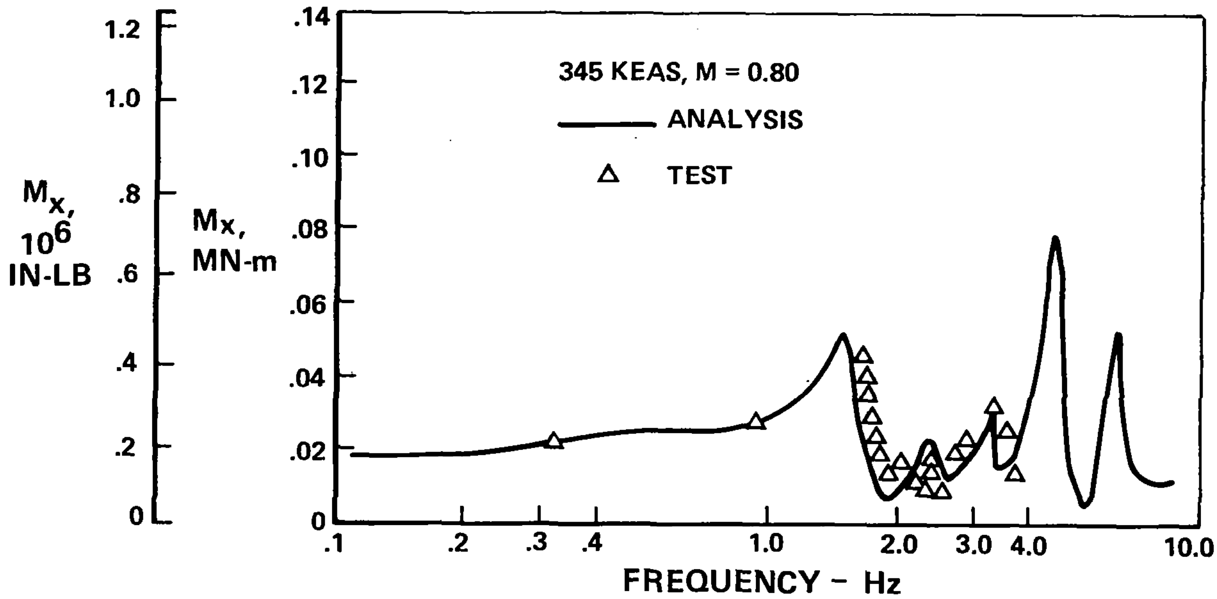


Figure 16.- Wing bending moment at BL 702/degree aileron.

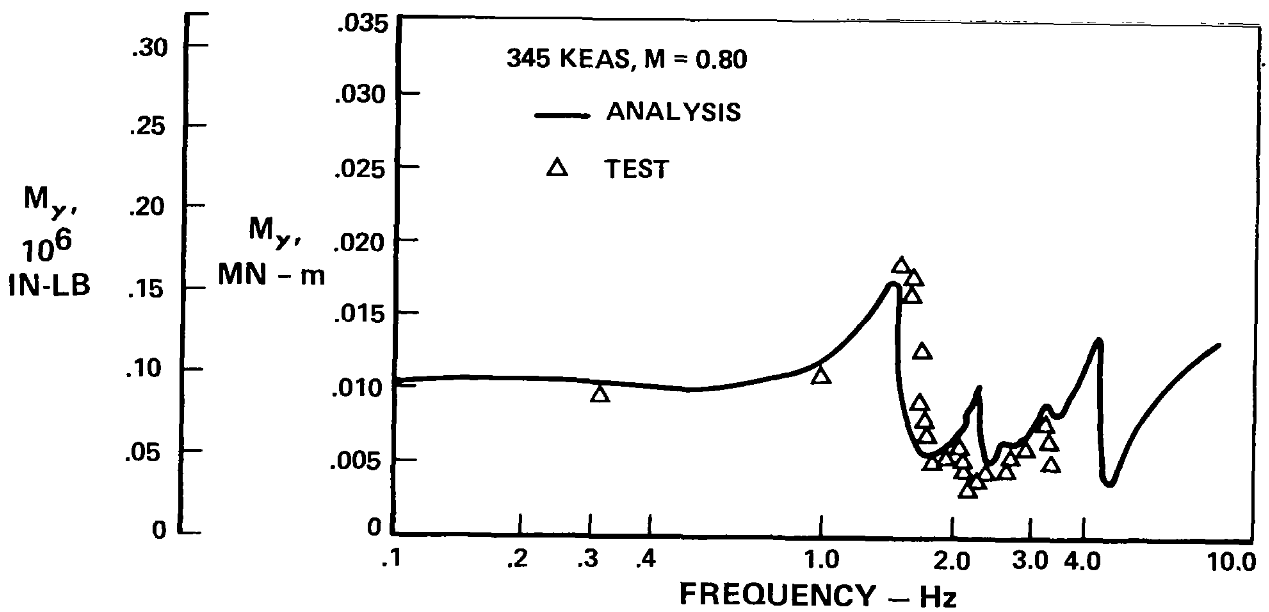


Figure 17.- Wing torsion moment at BL 702/degree aileron.

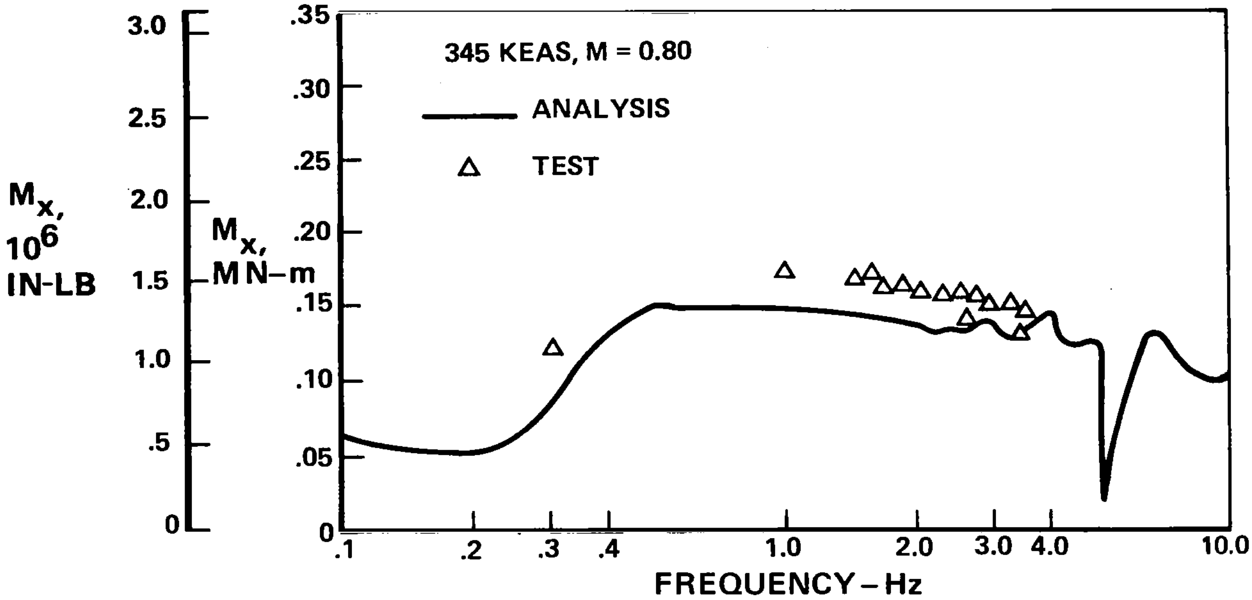


Figure 18.- Horizontal stabilizer bending moment at BL 126/degree stabilizer.

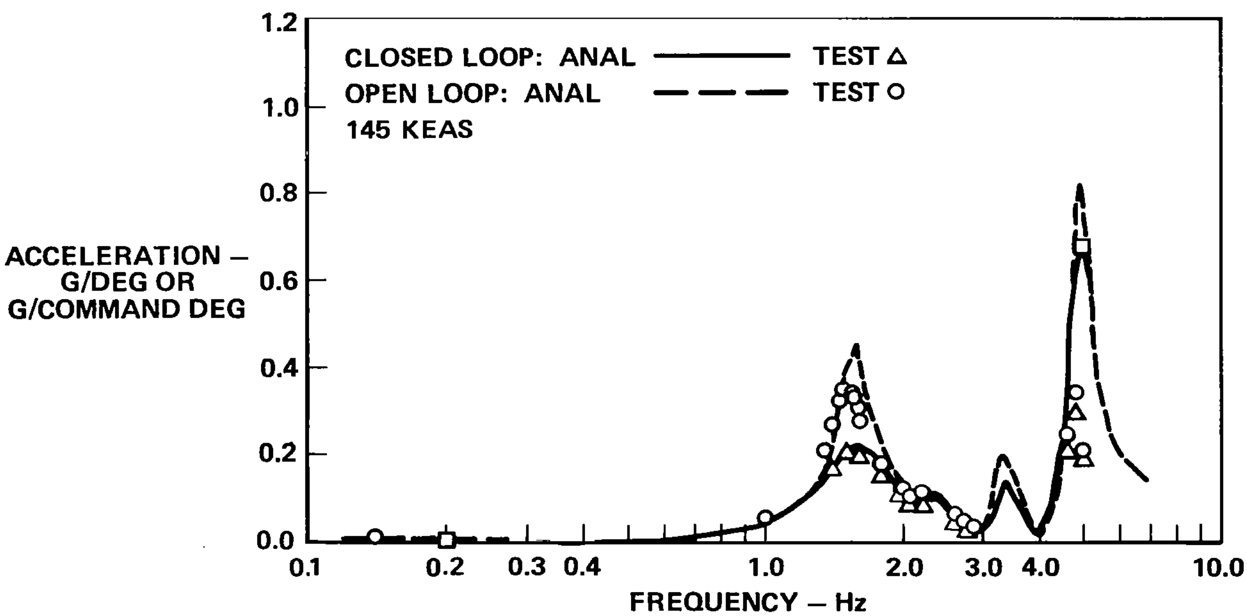


Figure 19.- ACS ON/OFF comparison wing-tip acceleration — aileron drive.

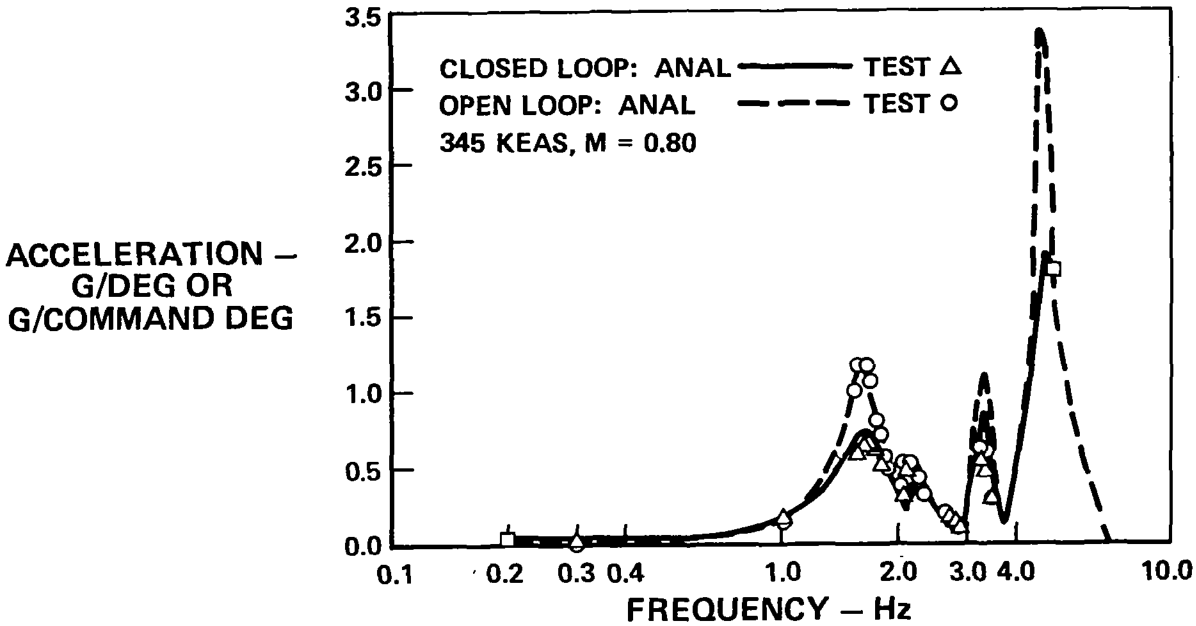


Figure 20.- ACS ON/OFF comparison wing-tip acceleration — aileron drive.

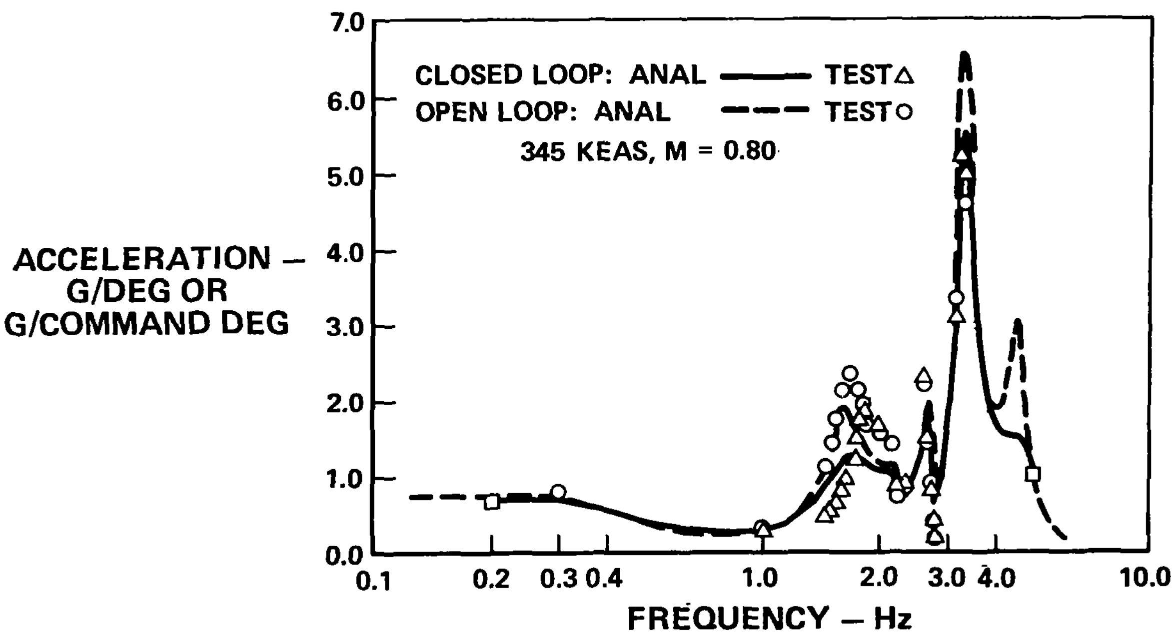


Figure 21.- ACS ON/OFF comparison wing-tip acceleration — stabilizer drive.

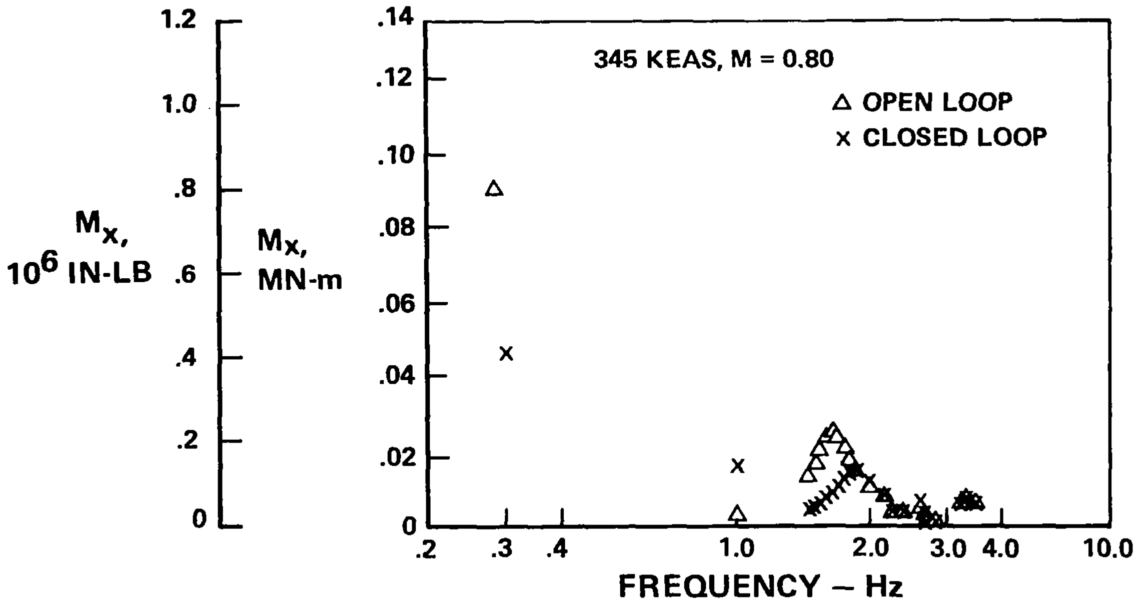


Figure 22.- Wing bending moment at BL 487/volt command stabilizer.

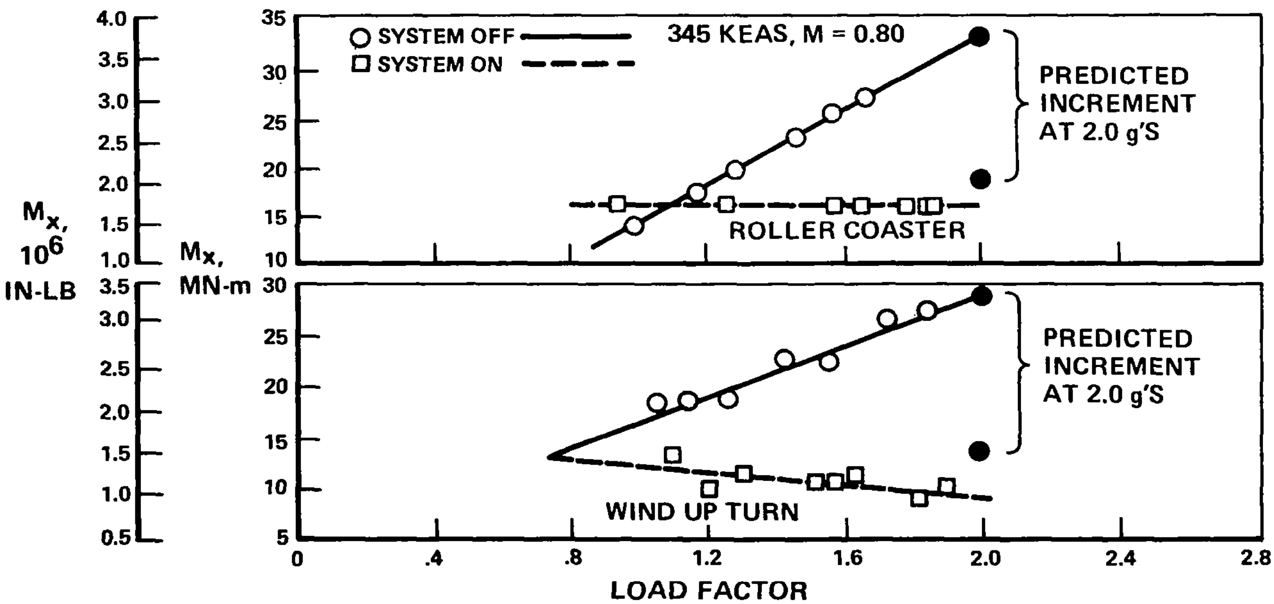


Figure 23.- BL 702 bending moment as function of load factor LC-1M.

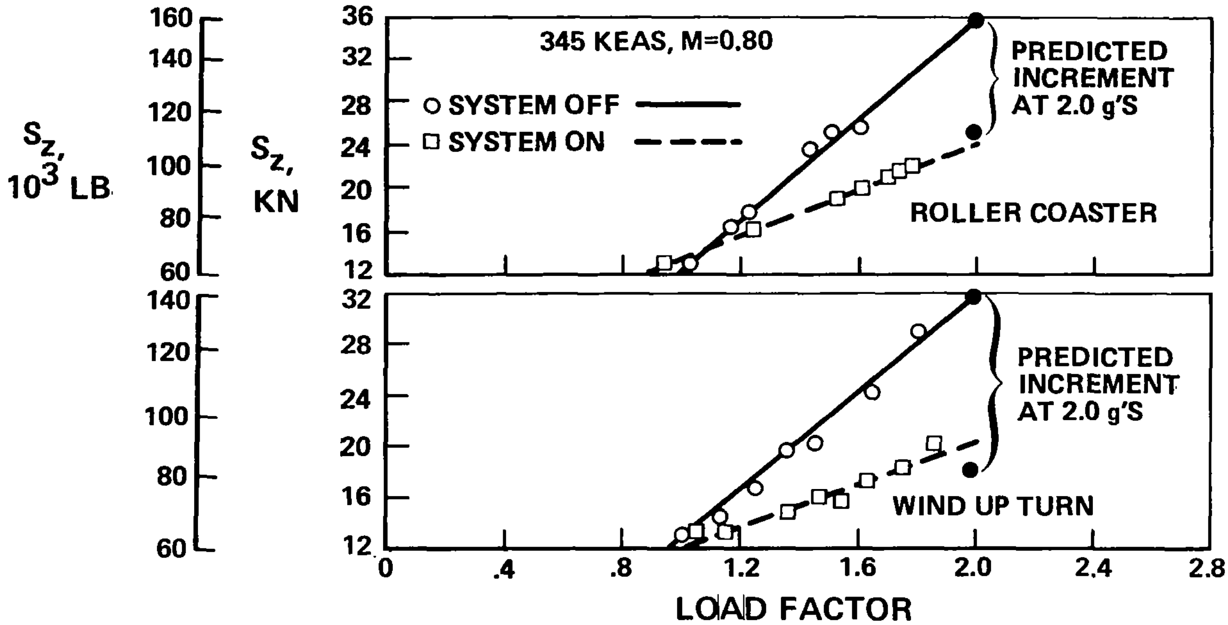


Figure 24.- BL 702 shear as function of load factor LC-1M.

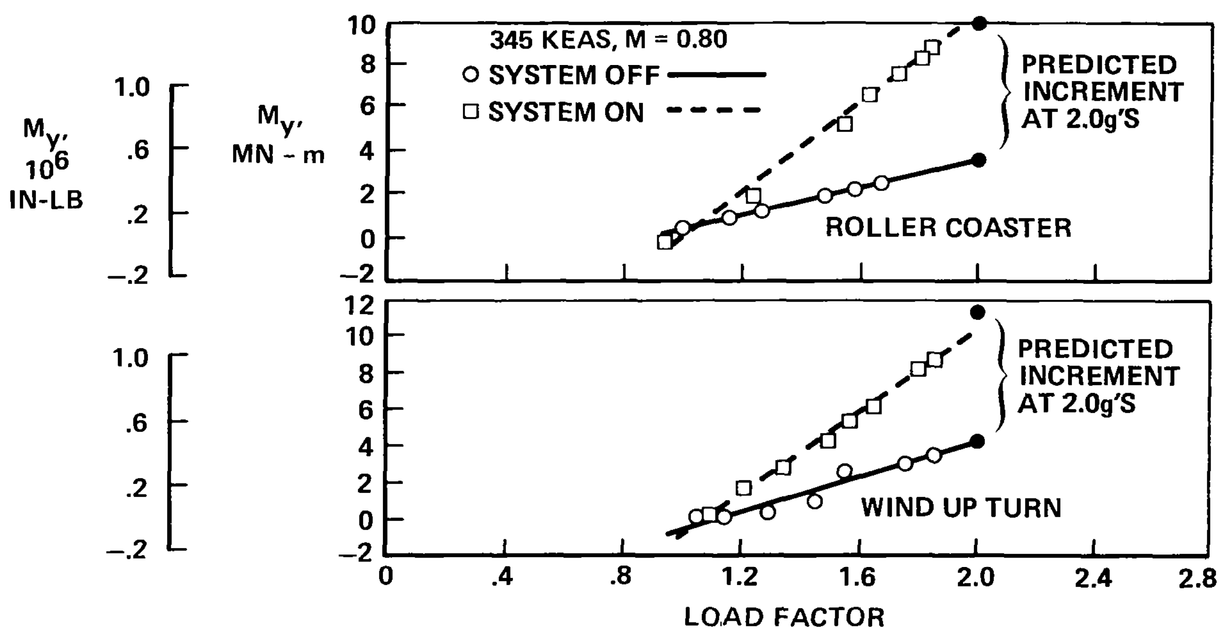


Figure 25.- BL 702 torsion moment as function of load factor LC-1M.

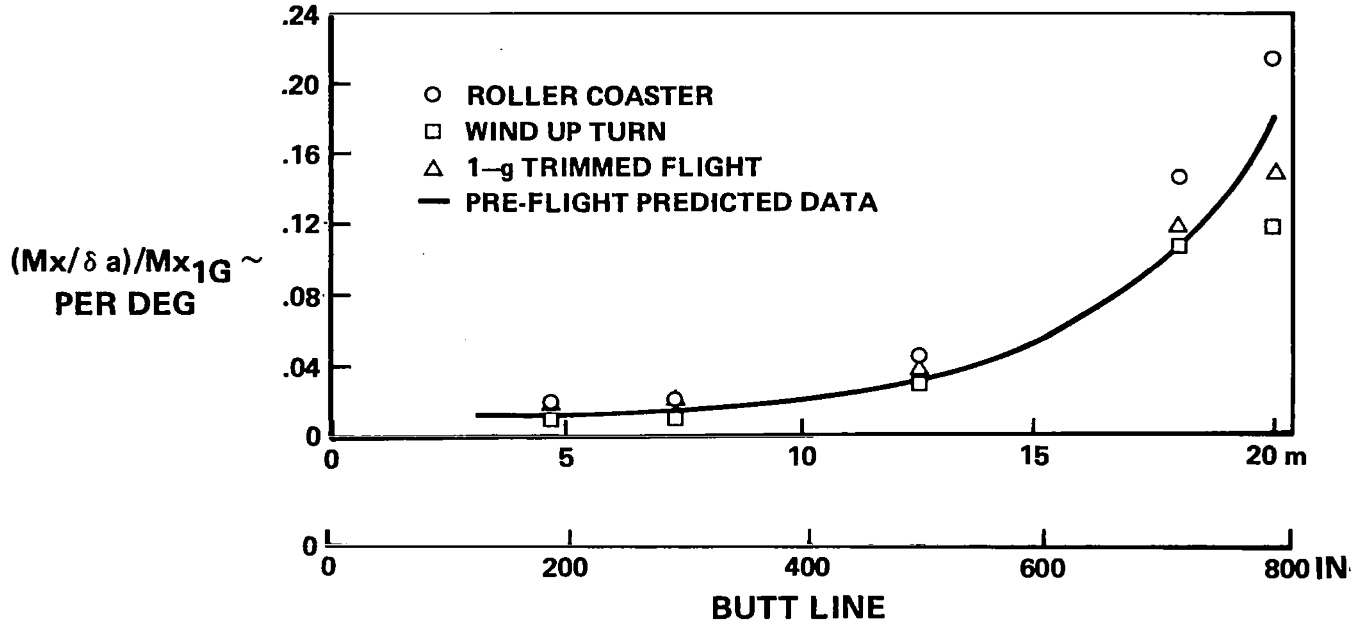


Figure 26.- Relative bending moment.

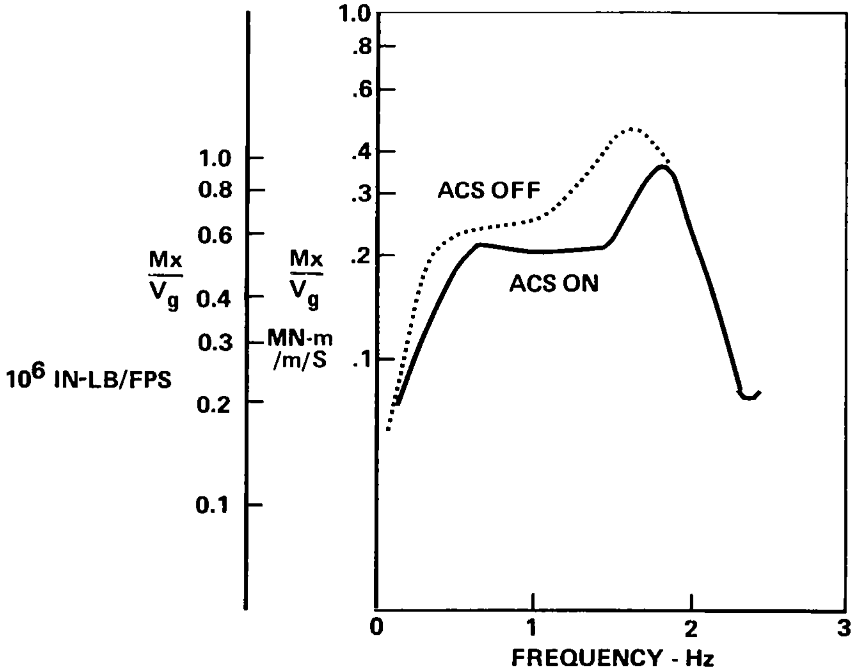


Figure 27.- Wing load in turbulence.

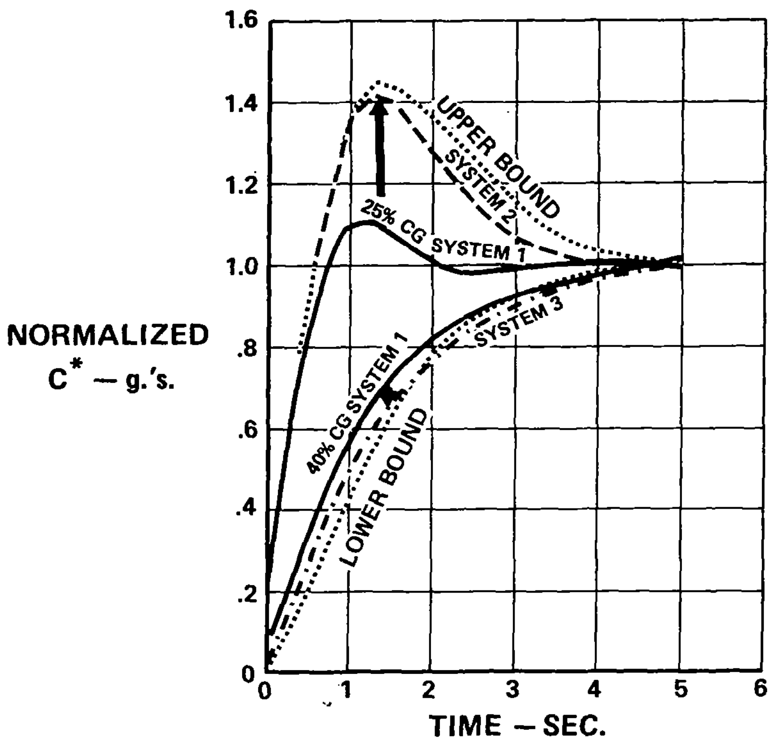


Figure 28.- Effect of feed forward on C* response (cruise).

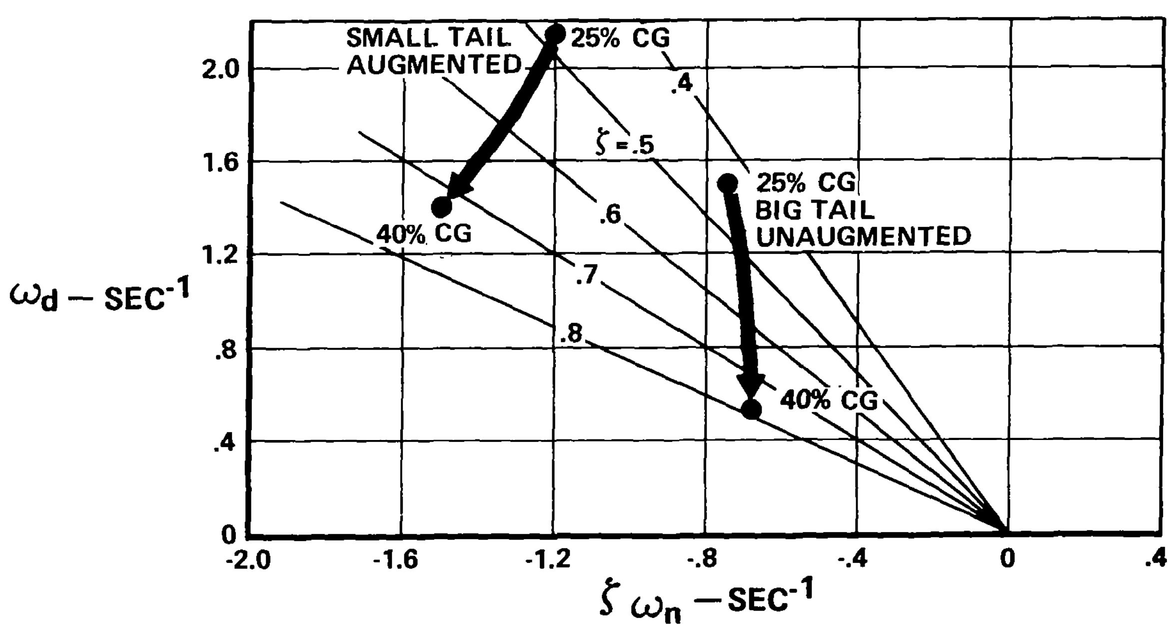


Figure 29.- Root loci — baseline and augmented small tail (cruise).

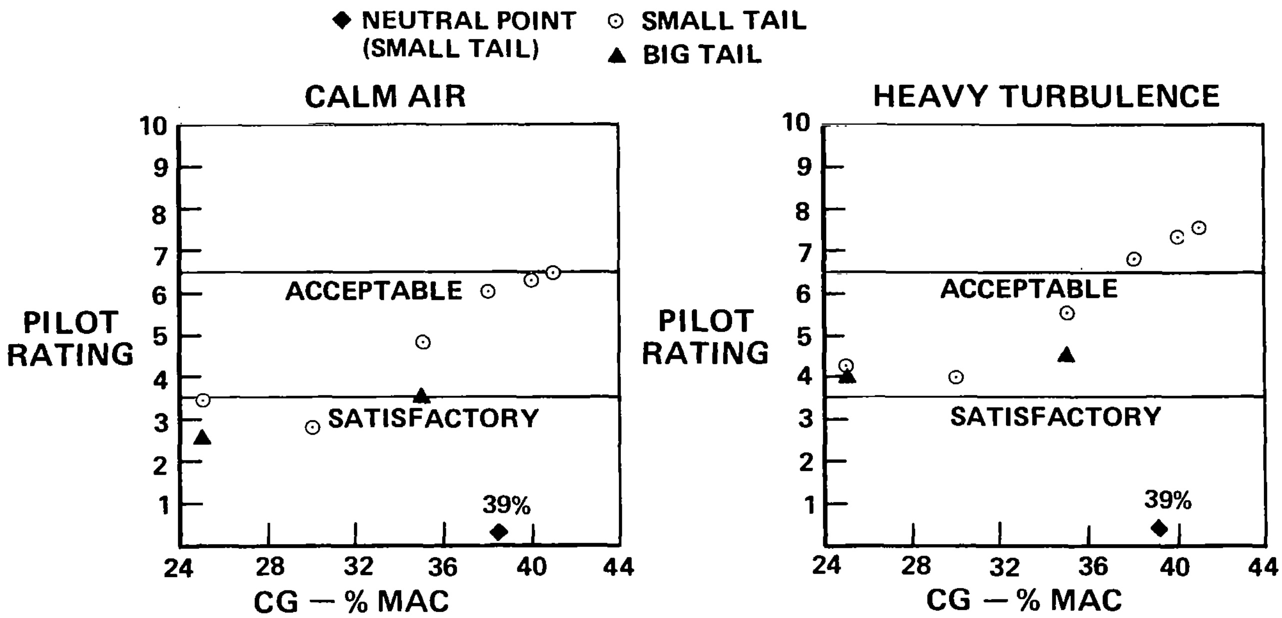


Figure 30.- Unaugmented cruise flying qualities.

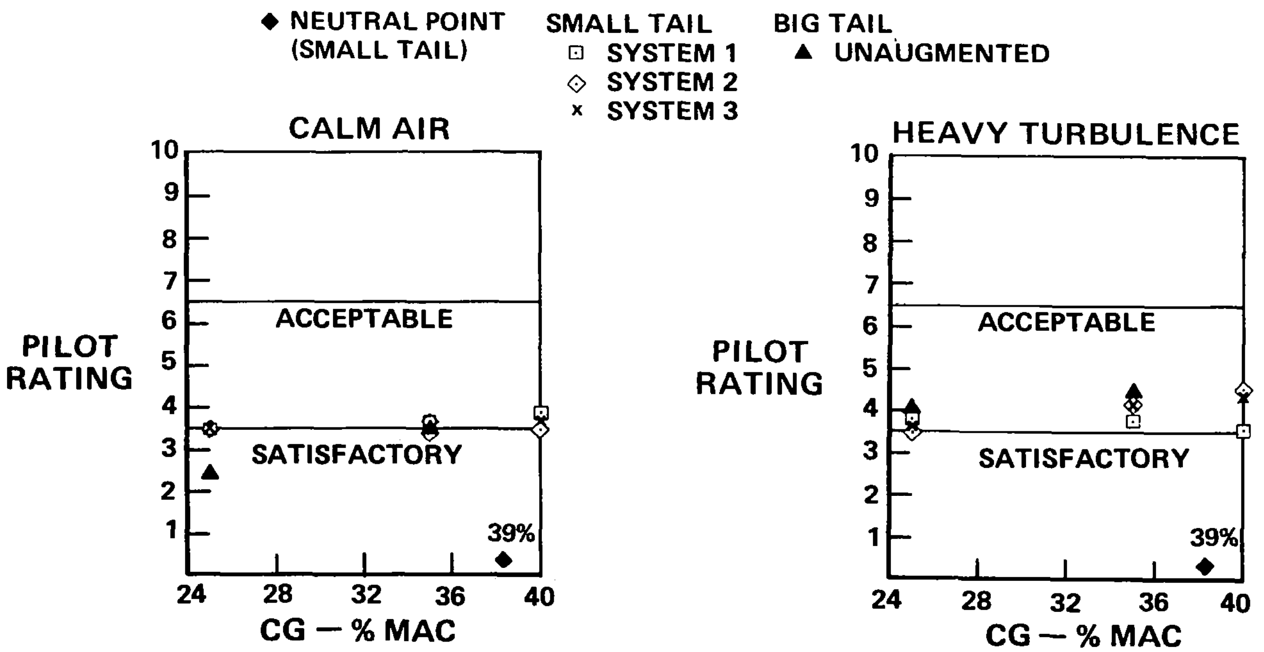


Figure 31.- Augmented cruise flying qualities.

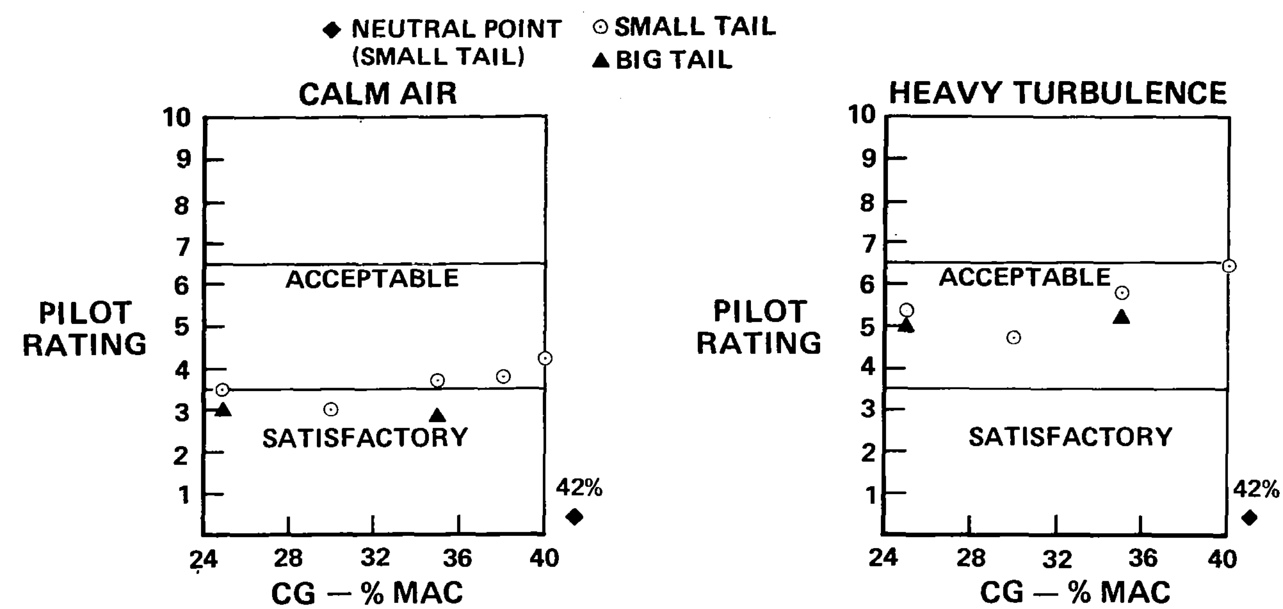


Figure 32.- Unaugmented approach flying qualities.

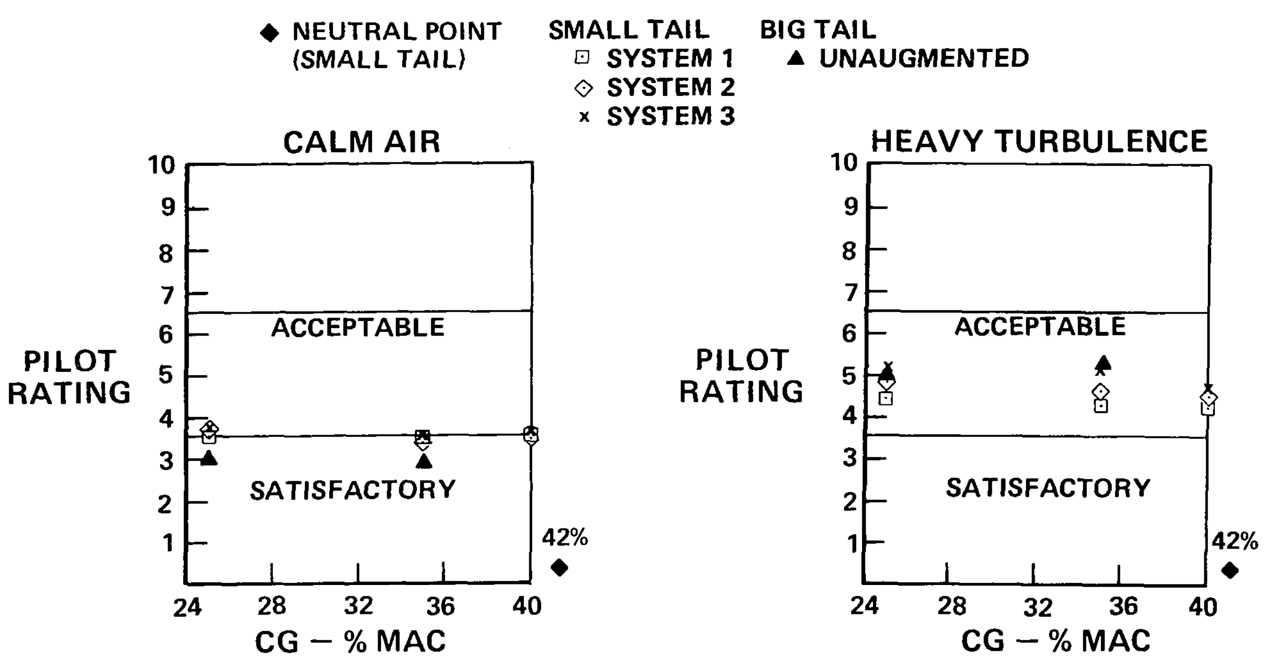


Figure 33.- Augmented approach flying qualities.

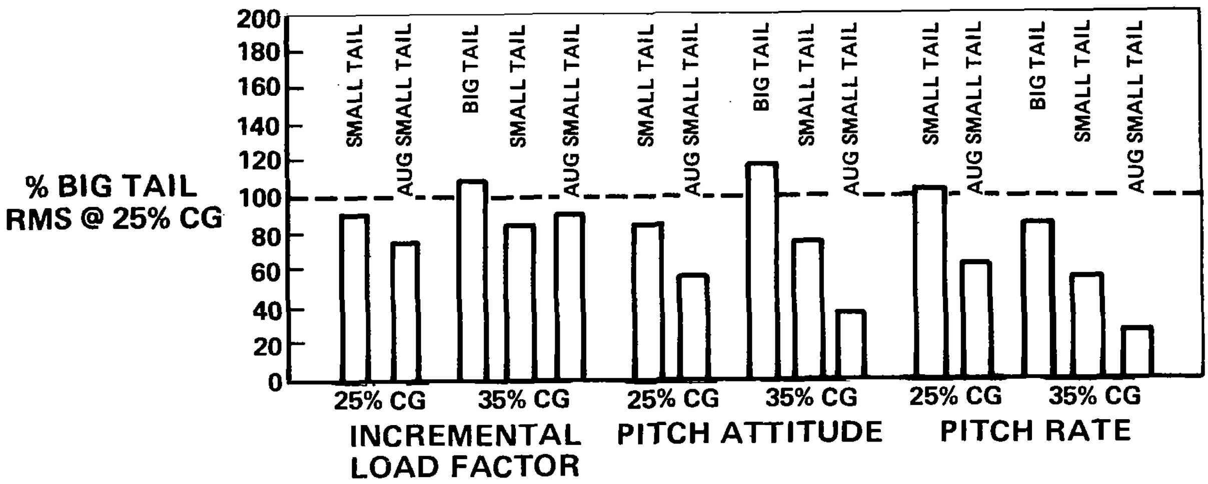


Figure 34.- RMS sirframe response — cruise.

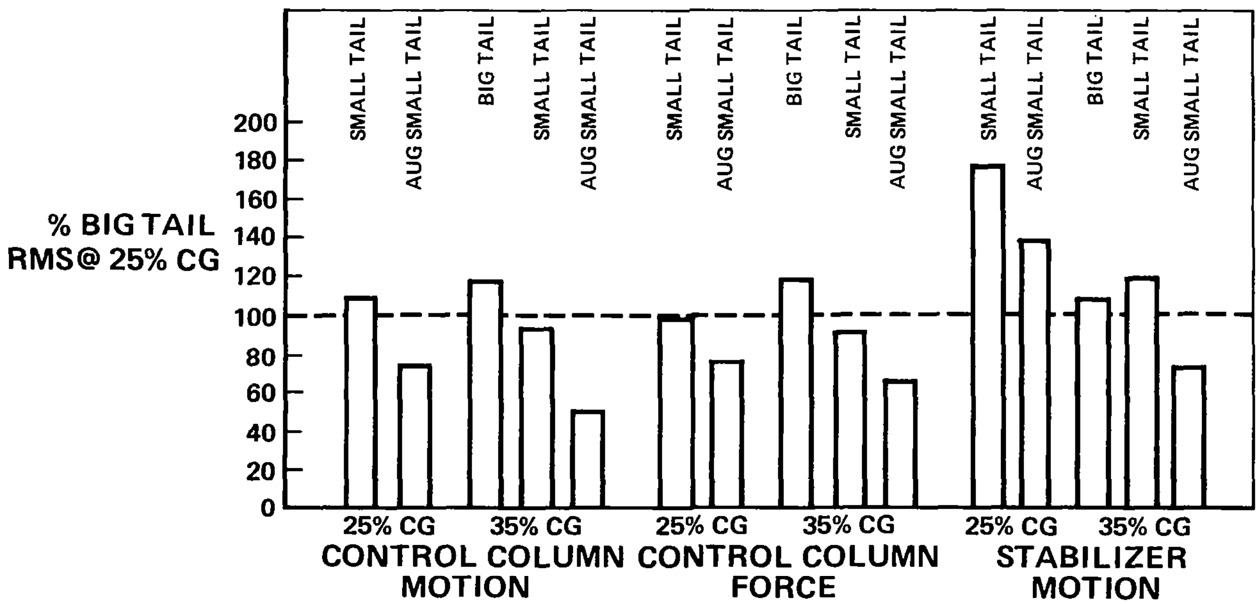


Figure 35.- RMS control activity — cruise.